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SIMULATED EFFECTS OF GROUND-WATER MANAGEMENT ALTERNATIVES FOR THE SALINAS VALLEY, CALIFORNIA

By *Eugene B. Yates*

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 87-4066

Prepared in cooperation with the
MONTEREY COUNTY FLOOD CONTROL
AND WATER CONSERVATION DISTRICT

4003-09

Sacramento, California
1988

DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

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CONVERSION FACTORS

For readers who prefer to use International System of units (SI) rather than inch-pound units, the conversion factors for the terms used in this report are listed below.

Multiply	By	To obtain
acres	0.4047	hectares
acre-ft (acre-feet)	.001233	cubic hectometers
acre-ft/yr (acre-feet per year)	.001233	cubic hectometers per year
ft (feet)	.3048	meters
ft/d (feet per day)	.3048	meters per day
ft^2/d (feet squared per day)	.0929	meters squared per day
(ft/d)/ft (feet per day per foot)	1.0000	meters per day per meter
ft/mi (feet per mile)	.1894	meters per kilometer
ft^3/s (cubic feet per second)	.02832	cubic meters per second
gal/min (gallons per minute)	.00378	cubic meters per minute
	.06308	liters per second
(gal/min)/ft (gallons per minute per foot)	.2070	liters per second per meter
inches	25.40	millimeters
in/yr (inches per year)	25.40	millimeters per year
mi (miles)	1.609	kilometers
mi^2 (square miles)	2.590	square kilometers

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level of 1929.

SIMULATED EFFECTS OF GROUND-WATER MANAGEMENT ALTERNATIVES FOR THE SALINAS VALLEY, CALIFORNIA

By *Eugene B. Yates*

ABSTRACT

A two-dimensional digital ground-water flow model was developed to analyze the geohydrology of the ground-water basin in the Salinas Valley. The ground-water model was calibrated for steady-state and transient simulations by comparing simulated with measured or estimated inflows, outflows, and water levels for 1970-81. Preliminary estimates of hydraulic properties and some inflows and outflows were adjusted during model calibration. The simulated mean annual water budget for the basin was 559,500 acre-feet per year each of outflow and inflow. Inflow components consisted of Salinas River recharge (38.3 percent), percolation of irrigation water (34.0 percent), small stream and Arroyo Seco recharge (20.9 percent), seawater intrusion (3.4 percent), and other sources (3.4 percent). Outflow components consisted of agricultural pumpage (91.5 percent), municipal pumpage (4.0 percent), and riparian phreatophyte evapotranspiration (4.5 percent).

For the steady-state calibration, 70 percent of the simulated water levels were within 9 feet of measured water levels for 1970-81. A sensitivity analysis determined the overall stability of the model results. The model input variable that probably contributes most to the uncertainty of the results is the quantity of ground-water recharge contributed by irrigation-return flow to the unconfined aquifer. A 15-percent change in the estimate of this variable causes an 11-percent change in the simulated river-seepage rate and a 6-percent change in the simulated seawater-intrusion rate.

The calibrated model was used to investigate several water-resources management alternatives. Projected pumpage increase at a rate of 1 percent per year for 20 years caused declines in mean annual water levels of 10 to 20 feet in some areas and an increase in seawater intrusion from 18,900 to 23,600 acre-feet per year. Pumpage decreases in the coastal area decreased seawater intrusion more effectively than pumpage decreases farther inland. When pumpage was decreased near the coast, seawater intrusion decreased one-seventh as much. When pumpage was decreased uniformly throughout the valley, the decrease in seawater intrusion was only one-fourteenth the decrease in pumpage. Simulations indicated that replacement of ground-water pumpage with imported surface water in a 9,000-acre service area near the coast would result in a decrease in seawater intrusion equaling nearly one-half the quantity of imported water. This further confirmed that the rate of seawater intrusion is most sensitive to pumpage near the coast.

INTRODUCTION

The coastal area of the Salinas Valley has undergone extensive agricultural development since the 1920's. Irrigation water for crop production is obtained almost exclusively from local wells. Because of the proximity of this area to the ocean, large rates of ground-water pumping cause the inflow of seawater into the aquifers. Consequently, many wells are contaminated by seawater and cannot be used as a source of irrigation water. Numerous management alternatives have been proposed to mitigate the problem of seawater intrusion. In general, these alternatives include decreased pumpage, surface-water importation, physical intrusion barriers, or a combination of these measures.

Purpose, Scope, and Approach

This study was done by the U.S. Geological Survey in cooperation with the Monterey County Flood Control and Water Conservation District. The purposes of this investigation were to identify and quantify the various types of flow into and out of the ground-water basin and to describe the physical processes that control them. The hydrologic analysis included development of a two-dimensional digital flow model. One of the goals of the study was to update and improve a previous digital model of the basin. This report presents the results of the investigation.

Mathematical equations that describe hydrologic processes and hydrologic data from the Salinas Valley were used in the model to simulate ground-water levels and the rate of seawater intrusion. The rate of seawater intrusion was estimated from the aquifer characteristics and the hydraulic-head gradient near the coast. The model was calibrated to accurately simulate measured historical flow rates and water levels. Data used in the model were adjusted to simulate conditions that would exist under each of the proposed management alternatives.

The data used in the model were selected from extensive information presently available for the Salinas Valley. Additional field measurements were not made.

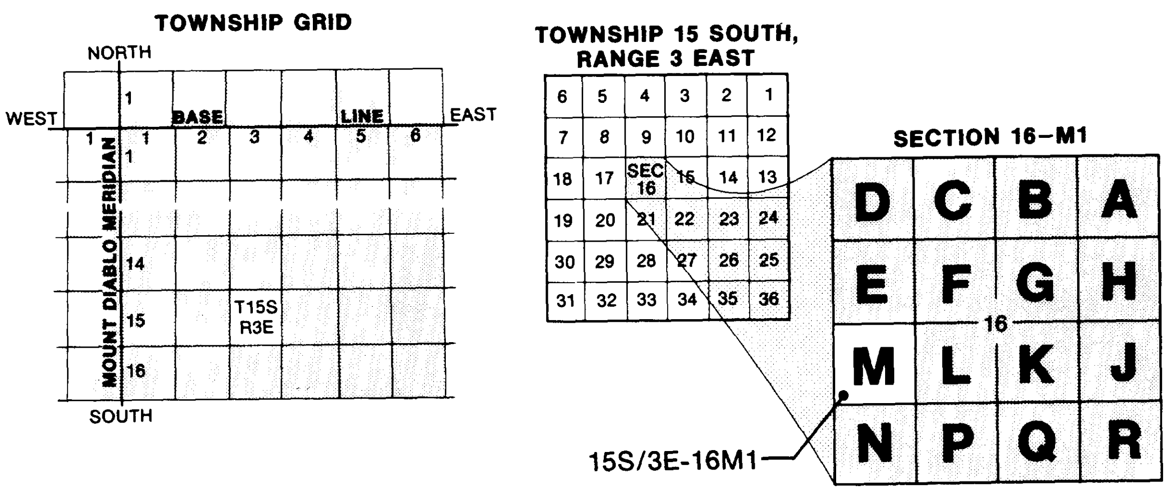
Previous Investigations

The development of the model and data used in this study closely parallels that of an earlier model by Durbin and others (1978). In essence, the present model constitutes a major revision of the previous one, which in this report will be referred to as "the previous model," and cited appropriately. To avoid unnecessary repetition, information transferred unchanged from the previous model to the present one will be discussed only briefly.

For more thorough derivations and descriptions of these data, the reader is referred to Durbin and others (1978). New or revised data and algorithms used in the present model will be fully described in this report.

Well-Numbering System

Wells are numbered according to their location in the rectangular coordinate system used for subdivision of public land. For example, in the well number 15S/3E-16M1, the part of the number preceding the slash indicates the township (T.15 S.), the part of the number immediately following the slash indicates the range (R.3 E.), the number following the hyphen indicates the section (sec. 16), and the letter following the section number indicates the 40-acre parcel within the section, according to the diagram below. The final digit is a serial number for wells in each 40-acre subdivision. The study area lies entirely in the southeast quadrant of the Mount Diablo base line and meridian.



Acknowledgments

This hydrologic investigation benefited greatly from ideas and information contributed by numerous individuals and agencies. Special recognition is due to Timothy J. Durbin of S.S. Papadopulos and Associates, Inc., Davis, California, for his assistance in resurrecting the previous model and for his guidance in developing the present one.

DESCRIPTION OF STUDY AREA

The Salinas River is in the coastal mountains of central California and drains an area of about 4,400 mi^2. The river originates near Santa Margarita and flows 120 miles northward to the Pacific coast at Monterey Bay. The lower 70 miles of the river, from San Ardo to Monterey Bay, are in the Salinas Valley. The valley is underlain by permeable, water-bearing alluvium. The alluvium forms a continuous ground-water basin that constitutes the study area for this investigation (fig. 1). The study area lies entirely within Monterey County.

The Salinas Valley is roughly linear and trends northwest. It has a flat floor ranging from 3 miles in width near San Ardo to about 10 miles in width at Monterey Bay. The altitude of the valley floor is about 400 feet above sea level at San Ardo.

Mountains rise abruptly along both sides of the valley floor. The Diablo Range and the Gabilan Range lie along the northeast edge of the valley, and the Sierra de Salinas and the Santa Lucia Range flank the southwest edge. Ridge altitudes average about 2,500 feet on the northeast side and 4,000 feet on the southwest side. The mountains on both sides of the valley decrease to low hills near the coast.

Mean annual precipitation is about 10 inches along the valley floor between San Ardo and Gonzales. It increases gradually to about 16 inches between Gonzales and the coast. Mean annual precipitation increases rapidly toward the adjacent mountains, reaching a maximum of about 20 inches in the Gabilan Range and 60 inches in the Santa Lucia Range (Rantz, 1969). Precipitation in the valley is extremely seasonal. About 50 percent of the annual precipitation occurs between December and February, and 90 percent occurs between November and April (U.S. National Oceanographic and Atmospheric Administration, 1967-82).

GEOHYDROLOGY OF THE GROUND-WATER BASIN

Geology

The alluvium in Salinas Valley consists of a series of marine and nonmarine sedimentary formations resting uncomformably on igneous and metamorphic basement rocks. The sedimentary formations include the Paso Robles Formation of Pliocene and Pleistocene age, windblown sand deposits of Pleistocene and Holocene age, and recent stream deposits. Total alluvial thickness ranges from 200 feet near San Ardo to 2,600 feet near Gonzales (Durbin and others, 1978). Selected surficial geologic features of the Salinas Valley are shown in figure 2, and the maximum thickness of the alluvium is shown in figure 3.

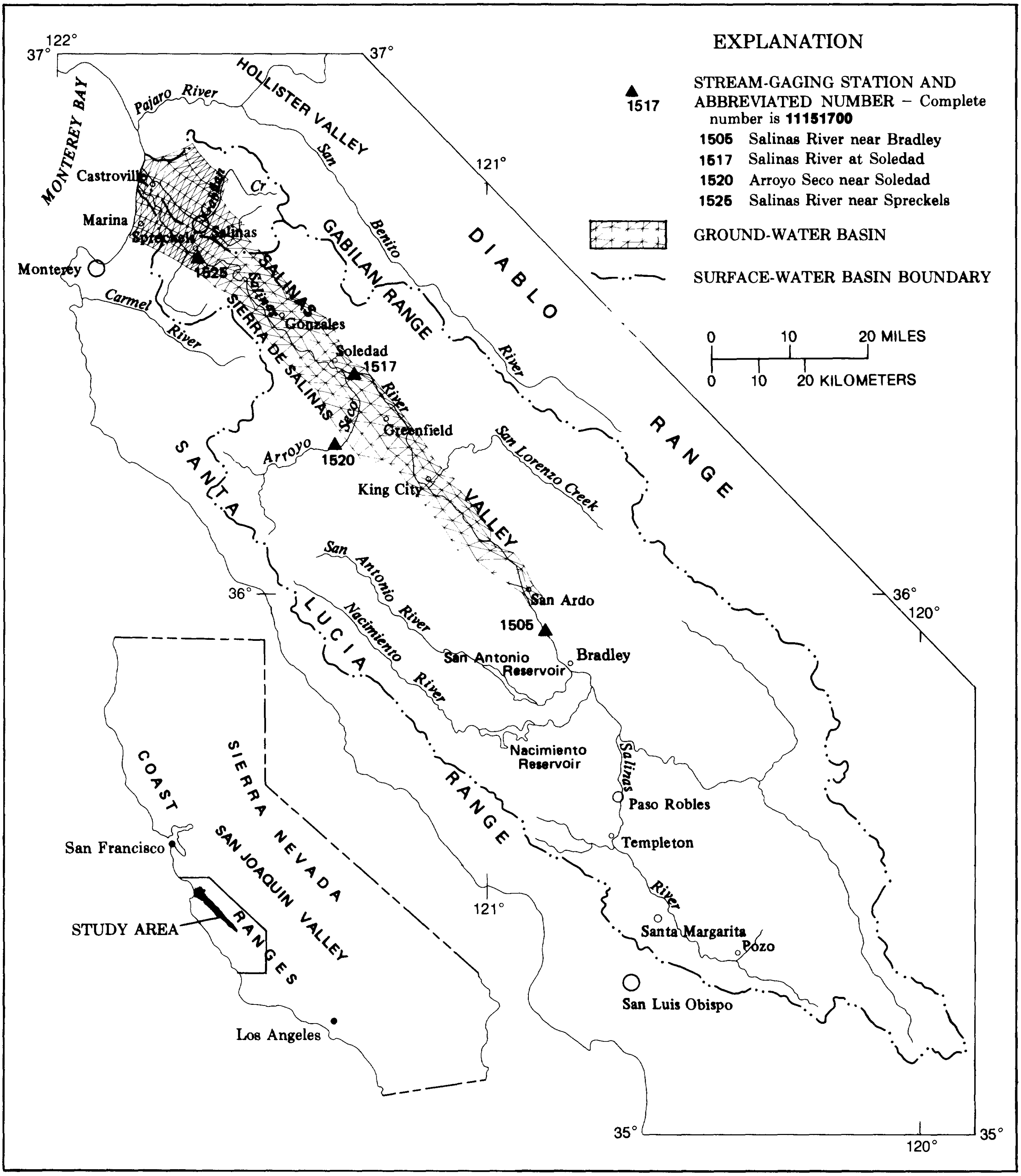
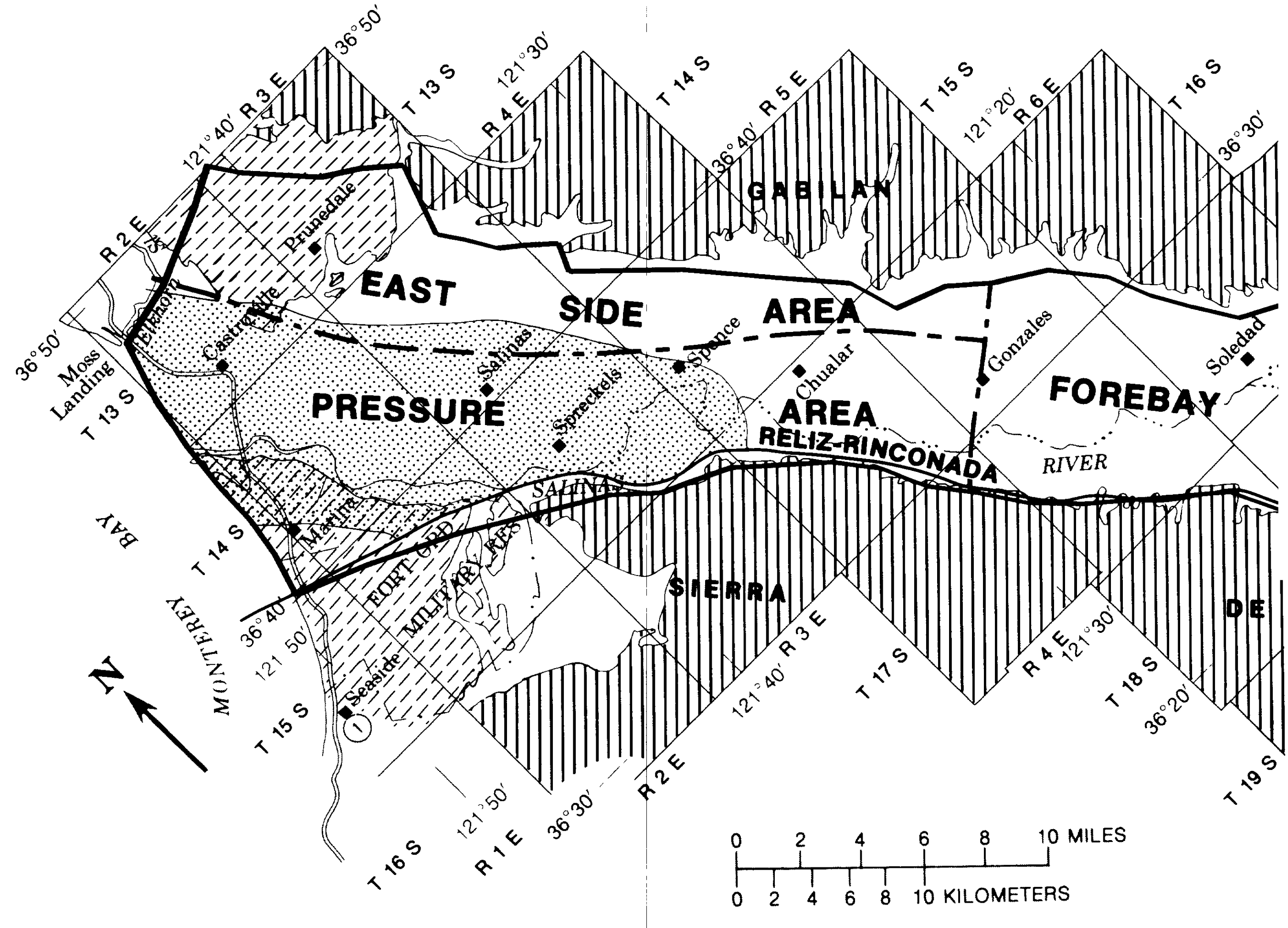


FIGURE 1. – Location and hydrologic features (modified from Durbin and others, 1978).


EAST
SIDE
AREA
PRESSURE
AREA
FOREBAY
GABILAN
SIERRA
RELIZ-RINCONADA
RIVER
SALINAS
FORT ORD MILITARY RES
MONTEREY
BAY
Moss Landing
Elkhorn
Castroville
Prunedale
Salinas
Spreckels
Spence
Chualar
Gonzales
Soledad
Marina
Seaside
N
0 2 4 6 8 10 MILES
0 2 4 6 8 10 KILOMETERS

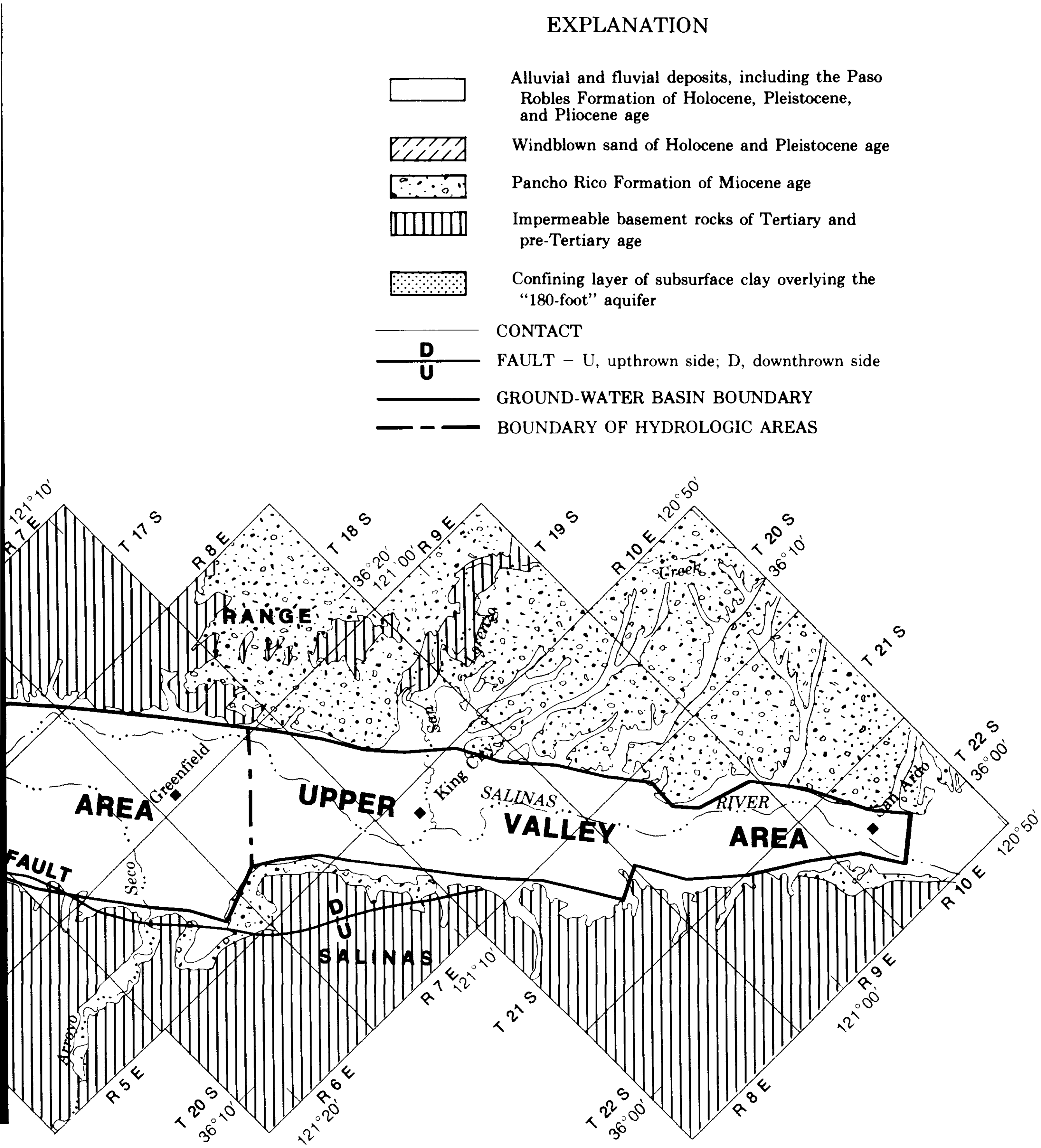
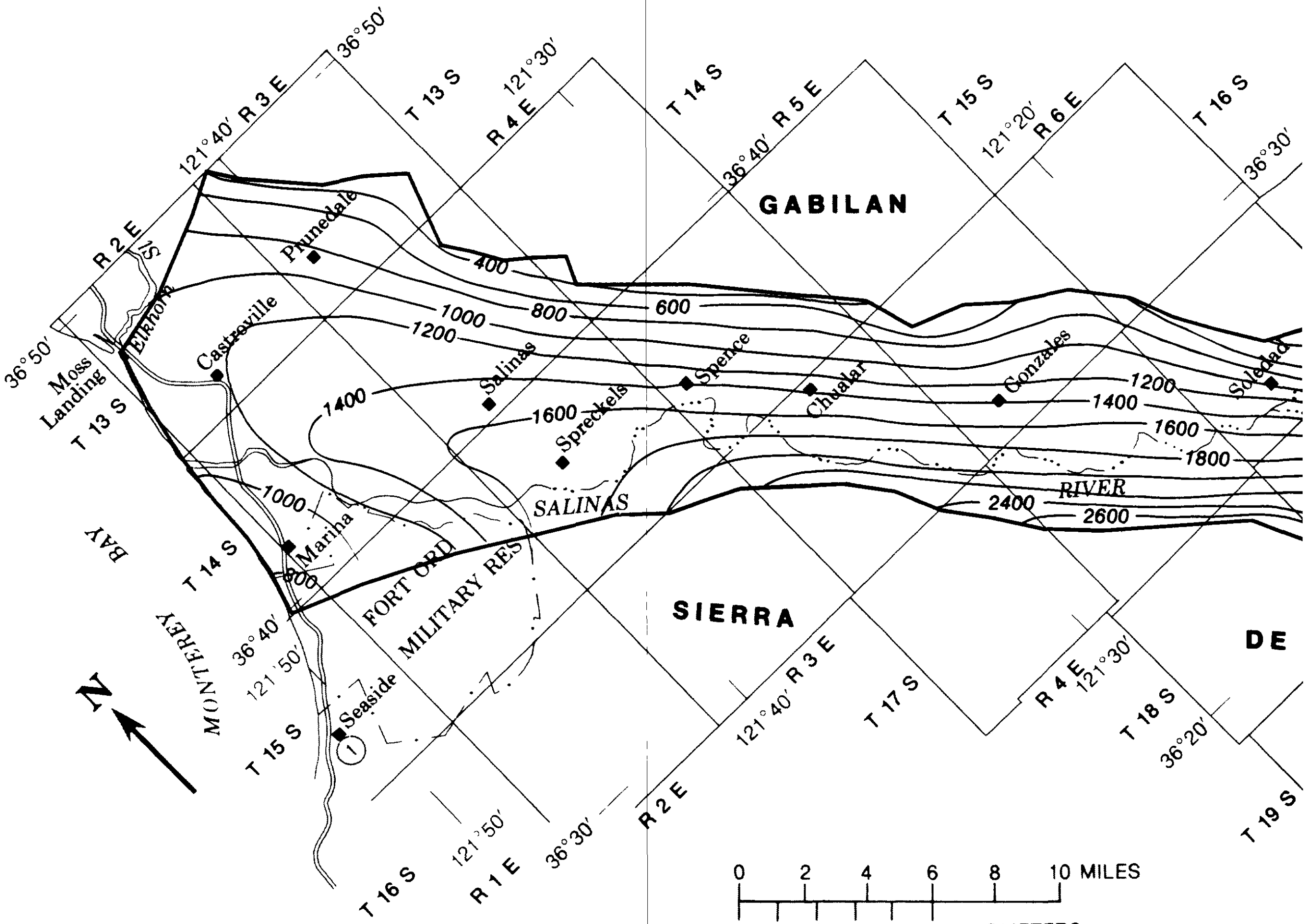


FIGURE 2. — Hydrologic areas and selected geologic features.


GABILAN
SIERRA
DE
SALINAS
RIVER
MONTEREY
BAY
FORT ORD
MILITARY RES
Prunedale
Castroville
Elkhorn
Moss Landing
Salinas
Spreckels
Spence
Chualar
Gonzales
Soledad
Marina
Seaside
400
600
800
1000
1200
1400
1600
1800
2400
2600
T 13 S
T 14 S
T 15 S
T 16 S
T 17 S
T 18 S
T 19 S
R 1 E
R 2 E
R 3 E
R 4 E
R 5 E
R 6 E
36°50′
36°40′
36°30′
36°20′
121°50′
121°40′
121°30′
121°20′
N
0 2 4 6 8 10 MILES
0 2 4 6 8 10 KILOMETERS

EXPLANATION

—400— LINE OF EQUAL THICKNESS OF GROUND-WATER BASIN – Interval is 200 feet

——— GROUND-WATER BASIN BOUNDARY

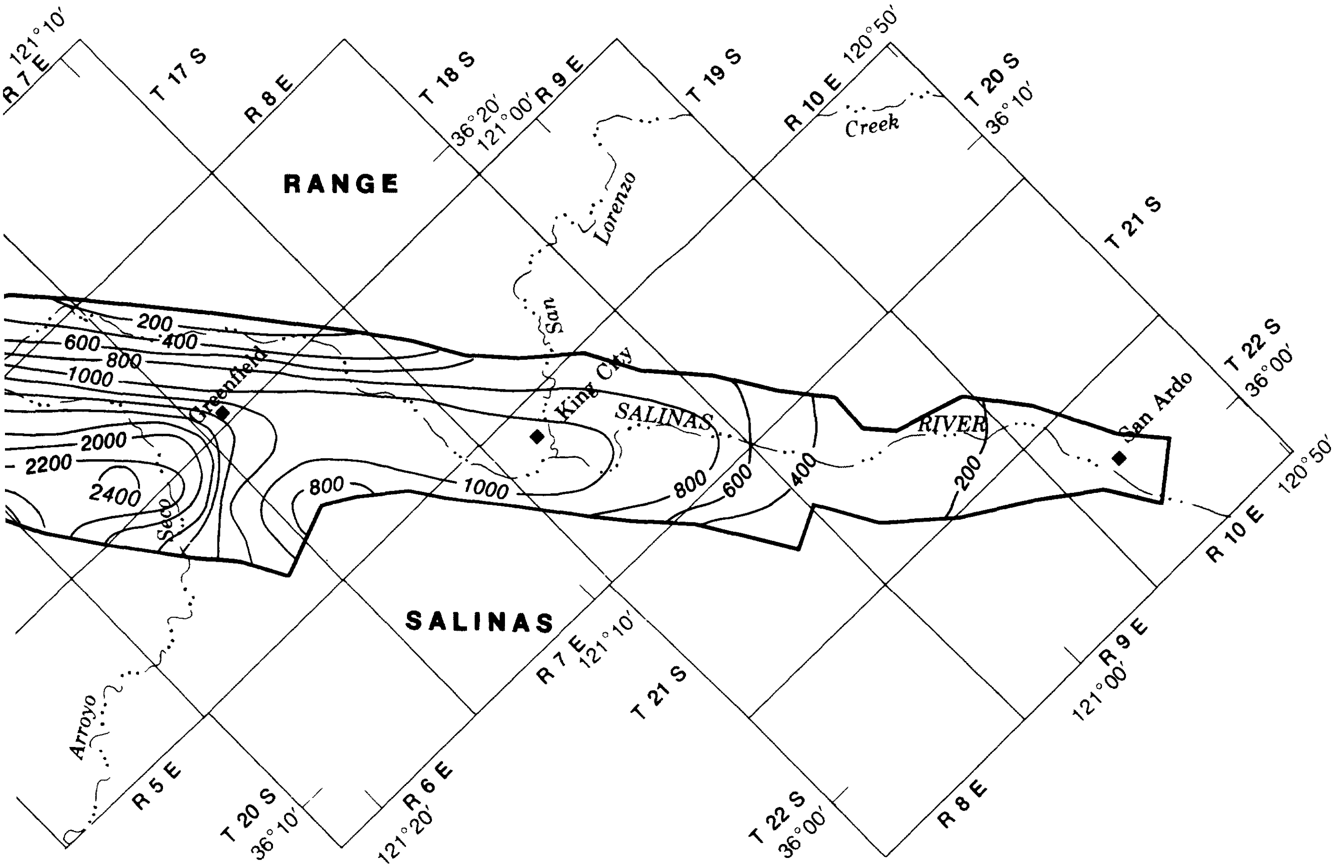


FIGURE 3. – Maximum thickness of the ground-water basin.

In the coastal area downstream from Gonzales, the stratigraphy consists of a complex assemblage of interfingered, lenticular clay, silt, and sand layers of varying thickness. Downstream of Chualar, relatively continuous layers of fine-grained estuarine sediments near the axis of the valley were deposited in the Pleistocene Epoch during periods of high sea level. These beds were partially dissected by streams and occasionally covered by aeolian dune sands during intervening periods of low sea level. However, clay layers are still continuous enough to create confined ground-water conditions in a large area near the coast (fig. 2).

Within the confined area, there are two intervals of relatively permeable sediments at depths of around 180 and 400 feet. Although these intervals do not form two distinct aquifers, and their depths and thicknesses vary considerably from place to place, they are commonly referred to as the "180-foot" and "400-foot" aquifers. They are the intervals that have been developed most extensively for water supply. The aquifers in the confined area (fig. 2) extend offshore several miles to submarine outcrop areas. The outcrops are hydraulically connected with the ocean and allow the flow of water into or out of the aquifer.

Upstream from Gonzales, the alluvium in the center of the valley consists primarily of fluvial sediments, including recent terrace remnants and flood-plain deposits. Along the sides of the valley, tributary streams have formed alluvial fans that interfinger with the fluvial deposits. The fans along the northeast side of the valley have a higher clay content and lower permeability than the fans along the southwest side.

Recent windblown sand deposits occur in several areas near the coast. The principal exposures of these deposits are in the hills north of Salinas and in a large area near the city of Marina and the military base at Fort Ord (Durbin and others, 1978).

Hydrologic Areas

Four hydrologic areas of the Salinas Valley ground-water basin have been designated by the California Department of Public Works (1946). The areas are referred to as: (1) Pressure Area, (2) East Side Area, (3) Forebay Area, and (4) Upper Valley Area (fig. 2). These areas were delineated on the basis of their hydrogeologic characteristics and are proposed as potential management zones for the implementation of water-resource management policies. Information for the following descriptions of the areas was obtained from Durbin and others (1978), Raymond Alsop (driller, Salinas, oral commun., 1984), and Robert Chappell (Chappell Pump and Supply, oral commun., 1984).

The complex stratigraphy of the Pressure Area exhibits varying degrees of confinement. The scale of spatial variability within the alluvial deposits is small enough that for the purpose of analyzing basinwide flow patterns, the deposits can be better described as a single, homogeneous, vertically anistropic unit, than as a sequence of individual aquifers and confining beds.

Specific capacities of wells perforated in the "180-foot" and "400-foot" aquifers typically range from 40 to 159 (gal/min)/ft. Recharge to the aquifers in the Pressure Area is from ground-water inflow from the Forebay Area, river seepage near Gonzales, seawater intrusion, ground-water inflow near Marina, small quantities of irrigation-return flow, and infiltrated precipitation.

The East Side Area is underlain by alluvial-fan deposits of lower permeability than the alluvial deposits in the Pressure Area. Specific capacities of wells range from 1 to 50 (gal/min)/ft, and ground-water levels decline throughout the summer pumping season. Ground water in the East Side Area is unconfined, and recharge is from streams associated with the alluvial fans and from ground-water inflow from the Forebay and Pressure Areas.

The alluvial deposits in the Forebay Area are generally more permeable than in the Pressure or East Side Areas. Specific capacities of wells range from 50 to 180 (gal/min)/ft. Ground-water recharge in this area is from Salinas River seepage, inflow of ground water from the Upper Valley Area, irrigation-return flow, and infiltration of precipitation. In addition, some ground-water recharge is from deep percolation through streambeds of tributary streams in the area, principally the Arroyo Seco.

The Upper Valley Area is the farthest upstream of the four areas and is underlain by the coarsest and most permeable sediments. Specific capacities of wells range from 80 to 200 (gal/min)/ft. Ground water in the Upper Valley Area is unconfined and recharge is from ground-water inflow from the mountains to the northeast, percolation from the Salinas River and its tributaries, irrigation-return flow, and infiltration of precipitation.

Hydraulic Properties

Three multiple-well aquifer tests were done in 1967 to measure aquifer transmissivity and storage coefficient (Monterey County Flood Control and Water Conservation District, 1967). The tests were all within several miles of Chualar. The depths of the pumping wells ranged from 245 to 636 feet. The reported values of transmissivity ranged from 12,000 to 160,000 ft^2/d. Average values were 104,000 ft^2/d for two wells near the Salinas River and 33,000 ft^2/d for a well near the boundary between the East Side and Pressure Areas. Average storage coefficients ranged from 0.000116 to 0.000290.

Analysis of the pumping test results was difficult because of the complex geohydrology of the test area. Measured transmissivity tended to be lower for observation wells closer to the pumping well, possibly due to effects caused by partial penetration of the aquifer by the wells or vertical anisotropy of hydraulic properties. Because of slow drainage from alluvial materials above and below the pumping horizon, storage coefficients increased during the tests. The reported values are for early drawdown data. Also, effects due to leaky aquifer conditions and recharge from the Salinas River were hypothesized but not separately measured or included in the analysis. Finally, without an accurate estimate of the saturated aquifer thickness affected by the pumping test, the transmissivity values cannot be reliably converted into estimates of hydraulic conductivity.

Aquifer Geometry and Boundaries

The lateral boundaries of the ground-water basin are defined by the contact between the permeable alluvium and older basement rocks. Along the southwest side of Salinas Valley, this contact was assumed to correspond to the Reliz-Rinconada Fault (fig. 2). Offshore, the basin is bounded by the submarine outcrop of the Paso Robles Formation. The remaining boundaries correspond approximately to the outside edge of the hydrologic subareas (fig. 2).

Except in a few places, the basement rocks along the bottom and sides of the Salinas Valley are considered for this analysis to be impermeable. The boundaries of the basin along these contacts were designated as no-flow boundaries. It was assumed that inflow and outflow of ground water do not occur along these boundaries.

Permeable alluvium exists immediately adjacent to the basin boundary north of Prunedale, along the northwest end of the northeast side of the valley (fig. 2). However, a thick, localized clay bed associated with Elkhorn Slough prevents ground-water flow across the boundary in the upper 300 feet of alluvium (California Department of Water Resources, 1973). This area was assumed to be a no-flow boundary.

In the other places where permeable materials lie just outside the basin boundary, recharge or discharge occurs due to base flow of ground water across the boundary.

The base of the ground-water basin is the bottom of the permeable, unconsolidated alluvium, which in the Salinas Valley was assumed to correspond to the base of the Paso Robles Formation. The upper surface of the basin coincides with the water table in unconfined areas and with the uppermost confining layer in the confined area. The water table can fluctuate vertically in response to transient hydrologic conditions, but its maximum altitude is limited to the local land-surface altitude.

Baseline Period

An appropriate baseline period for the analysis of the ground-water system in Salinas Valley was selected on the basis of cumulative departures of annual discharge for the Arroyo Seco (fig. 4). Average annual discharge during the specified baseline period is the same as during the entire period of record if the line connecting the points corresponding to the first and last year of the baseline period is horizontal (see fig. 4). The 11-year period from October 1970 through September 1981 was selected as the baseline period. This period also is appropriate for ground-water system analysis because it is after the construction of the two reservoirs upstream from the study area and because it reflects recent ground-water pumping patterns.

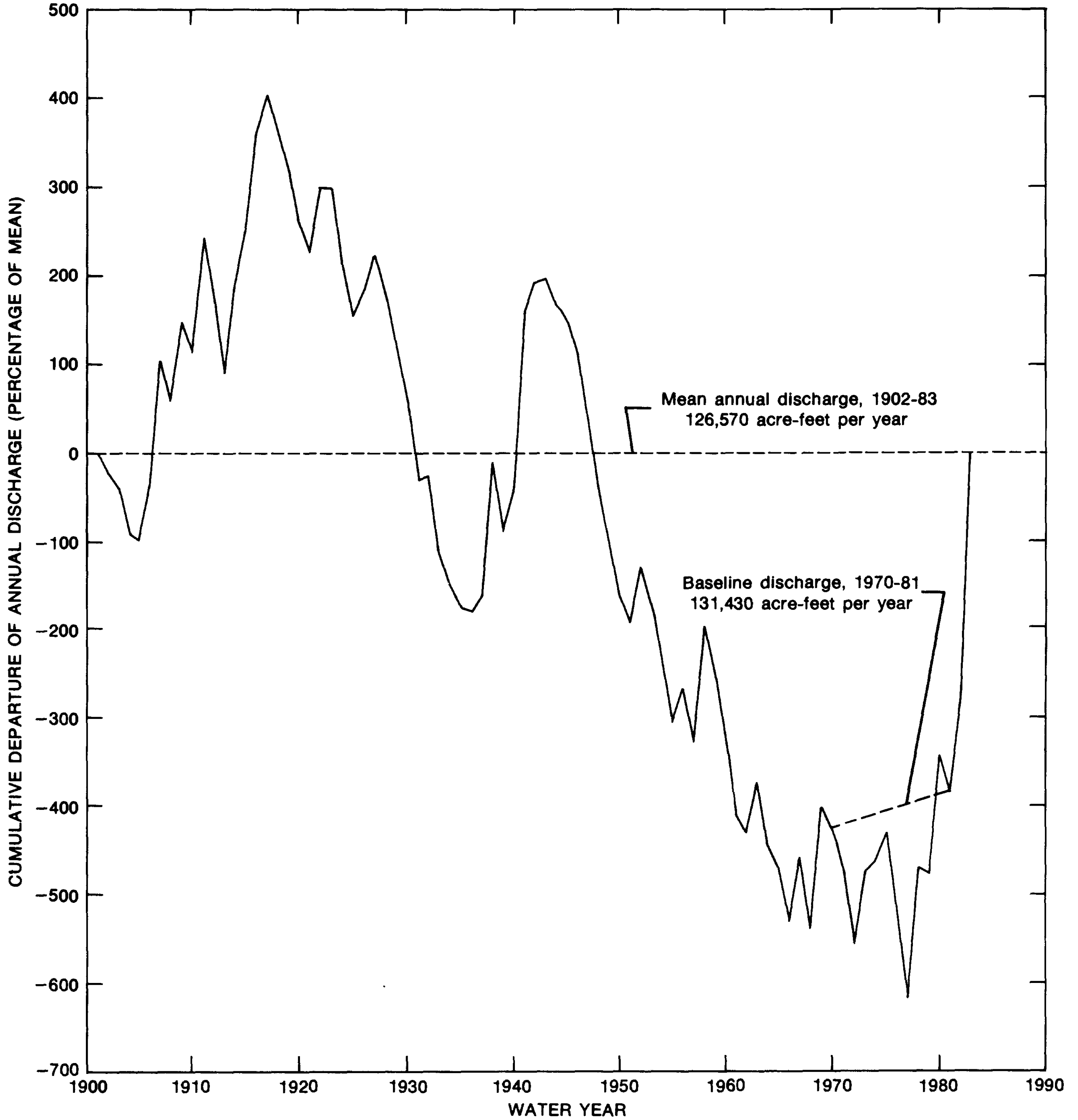


FIGURE 4. — Cumulative departure of annual discharge for the Arroyo Seco, 1902-83.

Inflow and Outflow

Precipitation

Direct recharge of ground water by deep percolation of precipitation is possible in areas where highly permeable surficial deposits overlie unconfined ground water and where sufficient precipitation occurs to overcome interception and evapotranspiration losses. In the previous study, direct recharge from precipitation was assumed to occur in two areas of the valley, the hills north of Prunedale and the old dunes south of Marina (fig. 2). These areas have highly permeable sandy soils and receive about 14 inches of precipitation per year. Recharge from precipitation for the two areas was estimated at 5,000 and 1,100 acre-ft/yr, respectively. Infiltrated precipitation was assumed to percolate slowly through an unsaturated zone before reaching the water table, resulting in a nearly constant rate of ground-water recharge (Durbin and others, 1978). Changes in the quantity and distribution of recharge from precipitation were not made for this study.

Surface Streams

Small Streams

Numerous small ephemeral streams drain the mountains on either side of the valley. As these streams flow across the valley floor, a large percentage of their flow seeps through the streambeds and becomes ground-water recharge. The remainder becomes tributary flow to the Salinas River. Much of the seepage occurs on alluvial fans, where the water table lies far below the streambed. Recharge passes through the unsaturated upper part of the alluvium before reaching the water table, and for this reason the rate of seepage flow was assumed to be independent of the ground-water level and constant with time.

Durbin and others (1978) estimated recharge from 58 small streams in the Salinas Valley by routing daily streamflow through a series of mass balance calculations. Seepage in each reach was assumed to be proportional to wetted area, vertical hydraulic conductivity of the streambed, and the vertical head gradient. Assuming a hydraulic gradient of unity, vertical hydraulic conductivity was estimated by a procedure in which calculated seepage from the Arroyo Seco was adjusted to match measured flow losses. The same routing procedure was applied in this study to seepage and tributary outflow for 1970-81, resulting in a hydraulic conductivity of 12 ft/d.

Because flow in the Arroyo Seco is highly seasonal and the unsaturated zone beneath the streambed is thin in many places, the rate of recharge to ground water also may be highly seasonal. For this reason, monthly values for tributary outflow and recharge from the Arroyo Seco were estimated and are shown in figure 5.

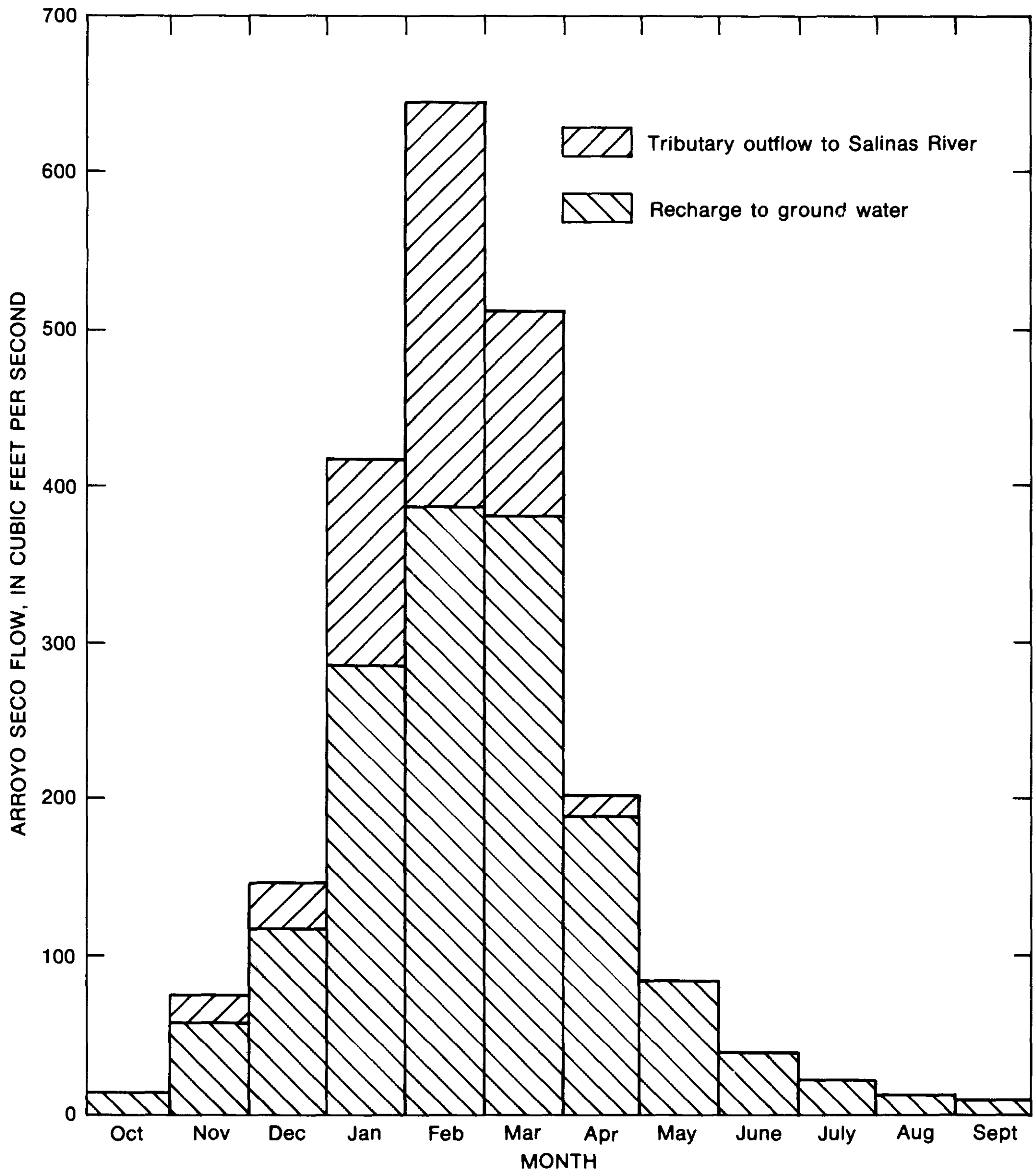


FIGURE 5. — **Average seasonal distribution of flow components for Arroyo Seco, 1970-81.**

Durbin and others (1978), estimated that long-term average annual ground-water recharge from all streams was 96,600 acre-ft/yr, of which 73,200 acre-ft/yr was contributed by the Arroyo Seco. Using the vertical hydraulic conductivity of 12 ft/d and the 1970-81 period as representative of long-term average conditions, the estimate used in this study was 117,000 acre-ft/yr, which includes 93,600 acre-ft/yr from the Arroyo Seco.

Outflow from small streams does not directly affect ground-water flow, but flows into the Salinas River, which does interact with the ground-water system. Durbin and others (1978) noted that San Lorenzo Creek and the Arroyo Seco together contributed 85 percent of the total tributary inflow to the Salinas River in the study area. To simplify their analysis, they grouped inflow from the other 56 tributaries with one or the other of the two large streams.

The results of the routings for the previous investigation were examined in this study to determine correlative relations between tributary flow of the Arroyo Seco and that of two tributary groups, which in this report will be referred to as the Arroyo Seco tributary group and the San Lorenzo tributary group. The relations were used to translate monthly Arroyo Seco flow into monthly tributary group inflow to the Salinas River. In previous investigations, average annual inflow to the Salinas River from the Arroyo Seco tributary group was calculated to equal 42,100 acre-ft/yr. Inflow from the San Lorenzo tributary group was 7,900 acre-ft/yr. The revised estimates used in this study were 37,500 and 10,300 acre-ft/yr, respectively.

The method used in this study to estimate ground-water recharge and tributary inflow for small streams other than the Arroyo Seco is less time-consuming but also less accurate than the routing procedure used for the Arroyo Seco (and used for all small streams) in the previous investigation. Because flow in small streams constitutes only about 4 percent of the total water budget for the basin, slight errors in flow and recharge components are assumed to be negligible.

Salinas River

The Salinas River differs from small streams in the study area because it is in direct hydraulic connection with ground water. An unsaturated zone does not separate river water from ground water in the underlying alluvium. Seepage can be into or out of the river, depending on whether the altitude of the stream surface is lower or higher than nearby ground-water levels.

Two reservoirs were built on major tributaries of the Salinas River upstream from the Salinas Valley to regulate winter floodflows in the Salinas River and to conserve water for summer use. Nacimento Reservoir was completed in 1956 and is about 30 miles upstream from San Ardo. San Antonio Reservoir was completed in 1967 and is about 22 miles upstream from San Ardo. Each reservoir has a capacity of about 350,000 acre-ft. Prior to construction of the reservoirs the Salinas River would usually dry up during the summer. Since then the reservoirs have been operated jointly to maintain flow during the summer downstream to the vicinity of Spreckels. River inflow at the basin boundary approximately equals the measured flow at the gaging station near Bradley. Average flow at the Bradley station for 1970-81 was 507 ft^3/s.

Average ground-water recharge for 1970-81 was estimated to equal 277,800 acre-ft/yr, based on differences in flow between the gaging stations at Bradley and Spreckels (Leedshill-Herkenhoff, 1984). This estimate included recharge from the Arroyo Seco.

Base Flow

In places where the ground-water basin is not bounded by impermeable bedrock, ground water can flow into or out of the basin. One such place is the northwestern end of the basin, where aquifers of the Salinas Valley extend offshore beneath Monterey Bay. Several miles from the coast, the aquifers intersect the sea floor in such a way that hydraulic continuity with the ocean is maintained. Water is free to flow into or out of the aquifers, depending on the hydraulic head gradient between the aquifers and the ocean. Landward head gradients are caused by onshore pumping and result in seawater intrusion.

Seawater contamination of wells was first noticed in the early 1930's, and by 1938 an increase in salinity had forced the abandonment of several wells along the coast (California Department of Public Works, 1946). The intrusion of seawater into aquifers has continued since that time. Areas of contamination with chloride concentrations greater than 500 mg/L are shown for the "180-foot" and "400-foot" aquifers in figure 6.

Since the construction of two water-supply reservoirs upstream from the Salinas Valley, ground-water levels throughout the valley have remained relatively stable and the rate of seawater intrusion has remained fairly constant.

In the previous investigation, the estimated rate of seawater intrusion was 11,000 acre-ft/yr. This value was generated by the simulation model as a residual in the mass-balance calculations (Durbin and others, 1978). It does not include intrusion in the area around Marina and Fort Ord. Other investigations estimated a rate between 11,000 and 20,000 acre-ft/yr based on historic water-quality changes and estimates of basinwide pumping overdraft (Leedshill-Herkenhoff, 1984).

Ground-water inflow also occurs near San Ardo, where the valley floor narrows to a width of about 3 miles. For the present study, a change was not made in the previous assumption that 1,000 acre-ft/yr of ground water enters the basin across this boundary (Durbin and others, 1978).

Another area of ground-water inflow occurs along the southern end of the northeast side of the study area, where the impermeable core of the Diablo Range is overlain by the Pancho Rico Formation of late Miocene age. This formation contains permeable sedimentary materials which lie in direct contact with the Salinas Valley alluvium (fig. 2). A rainfall-runoff analysis originally indicated that mean annual ground-water inflow from the Pancho Rico Formation is about 20,000 acre-ft/yr (Durbin and others, 1978). However, measured water levels along that boundary of the study area were much lower than simulated water levels reported in the previous study, suggesting that the quantity of inflow across the boundary was overestimated (Durbin and others, 1978, fig. 36).

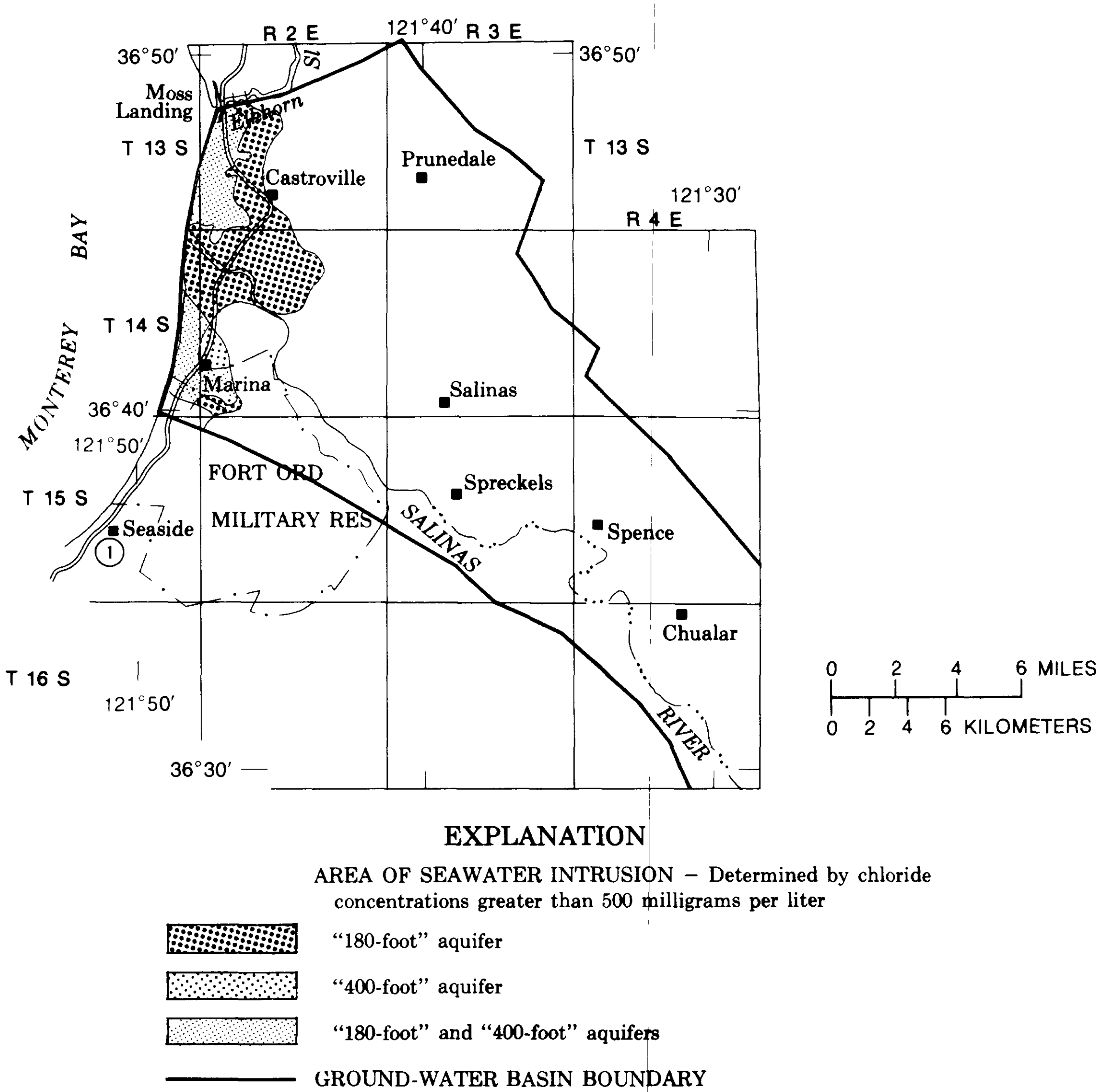


FIGURE 6. — **Areal extent of seawater intrusion in the "180-foot" and "400-foot" aquifers, 1983. (Modified from Leedshill-Herkenhoff, 1984, figs. 3-4 and 3-5.)**

The final area of ground-water inflow occurs along an 8-mile stretch of the southwestern boundary of the study area, between the Sierra de Salinas and Monterey Bay. In this area, the model boundary follows the subsurface extension of the Reliz-Rinconada (or King City) fault (fig. 2). In the previous study, the fault was assumed to be an impermeable barrier (Durbin and others, 1978).

The geohydrology of this part of the basin boundary was reevaluated for the present study. The offset of the fault decreases toward the ocean and affects only deep subsurface materials (California Department of Water Resources, 1973), which indicates that the boundary may be permeable and allow some ground-water inflow. Thorup (1984) also suggested that ground water moves across the fault. He included the wind-blown sands south of the fault among the ground-water recharge areas of the Salinas Valley. For this study, the previously described method for calculating recharge from precipitation on sandy areas inside the basin was applied to the sandy area lying south of the fault. The resulting estimate of ground-water inflow across the boundary was 1,000 acre-ft/yr.

Pumpage

Agricultural

Since the 1920's, increased agricultural development in the Salinas Valley has resulted in an increase in ground-water pumping. Ground water provides about 95 percent of the water used in the Salinas Valley (California Department of Water Resources, 1973). In 1920, about 600 wells supplied irrigation water for 50,000 acres (California Department of Public Works, 1946). By 1976, about 2,500 wells supplied irrigation water for 213,000 acres (Monterey County Flood Control and Water Conservation District, written commun., 1983). In the Pressure Area, nearly all potentially arable land is cultivated.

In the previous study, mean annual pumpage for the valley was estimated at 460,000 acre-ft/yr, based on an analysis of electricity use during 1969-71 (Durbin and others, 1978). Estimates for the present study were derived from a survey of land use conducted in 1976 by the California Department of Water Resources and the Monterey County Flood Control and Water Conservation District (written commun., 1983). Appropriate water-application rates were multiplied by land areas for each of 39 land-use categories. The water-application rates were derived from field studies of various crops grown in the Salinas Valley during 1962-71. The rates are mean values for normal climatic conditions. The water-use survey indicated that mean agricultural water use in the study area was 512,200 acre-ft/yr.

In many agricultural areas, a significant percentage of applied irrigation water percolates past the crop-root zone to the underlying water table. If the irrigation water is obtained from wells, the net quantity of ground-water extraction is less than the gross quantity actually pumped from the wells. In the previous study, 45 percent of agricultural pumpage was assumed to return to the aquifer. This percentage was obtained, in part, by model calibration. Irrigation-return flow in the confined part of the Pressure Area was assumed to flow laterally to the edge of the confining layer before percolating to the water table (Durbin and others, 1978).

Well logs and geologic cross sections of the confined area do not indicate that the shape or extent of the confining layers would induce significant lateral flow of irrigation-return water (California Department of Water Resources, 1973; Richard Thorup, geologist, Monterey, written commun., 1984). Irrigation-return flow in the Salinas Valley has not been measured, but the percent of applied water that percolates past the root zone is known to vary considerably with crop type, soil texture, and irrigation method.

Irrigation-return flow typically ranges from 20 to 50 percent of applied water for many areas in California, (California Department of Water Resources, 1984). A comparison of estimated evapotranspiration of applied water in the Salinas Valley (California Department of Water Resources, 1975) with estimates of applied water (Monterey County Flood Control and Water Conservation District, written commun., 1984) indicates that between 7 and 60 percent of applied water percolates to the water table.

Agricultural pumpage varies seasonally and from year to year. The average seasonal pumpage distribution estimated by Durbin and others (1978) from electrical-power consumption also was used in the present study (fig. 7). For annual variations, the present study used a functional relation between annual agricultural pumpage and precipitation to adjust mean annual pumpage values according to the climatic conditions prevailing in any given year. The assumed relation between annual agricultural pumpage and precipitation during

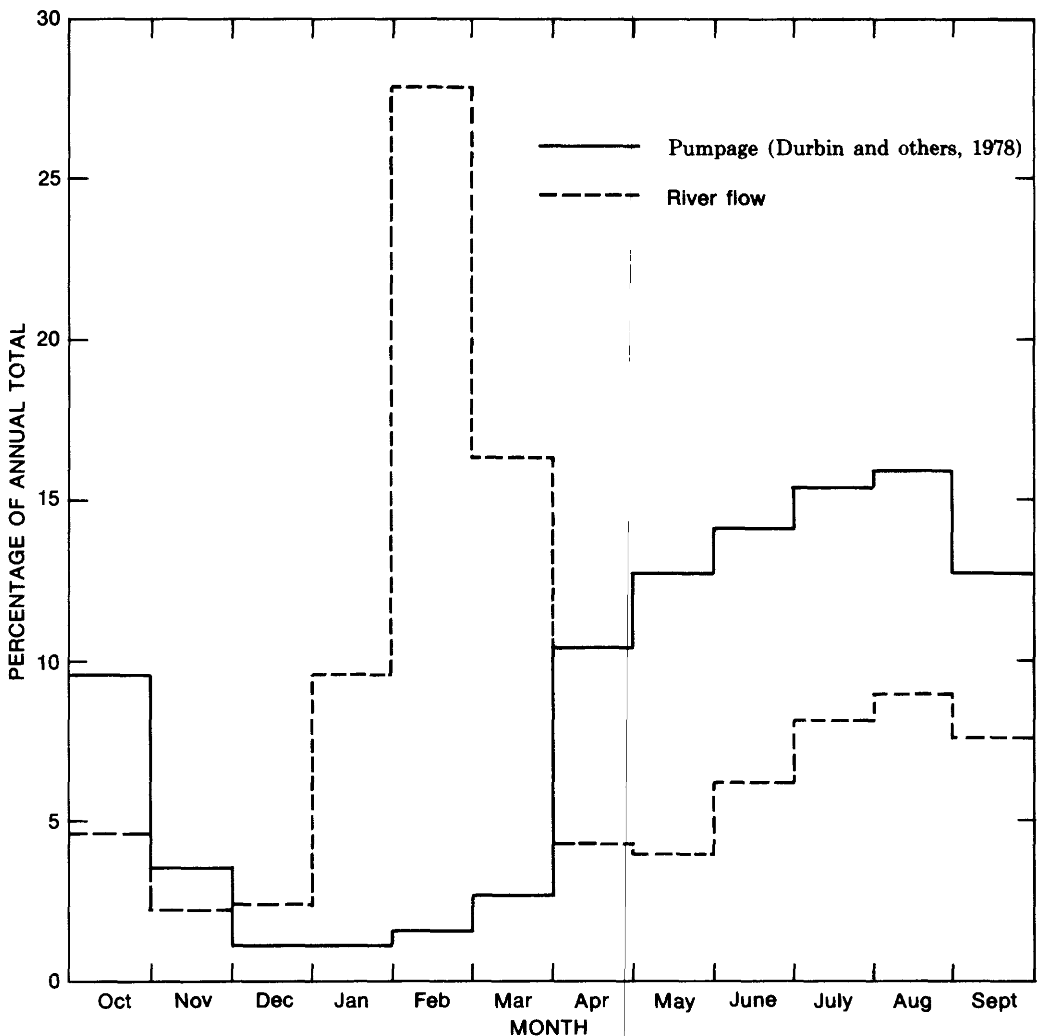


FIGURE 7. — Flow in the Salinas River near Bradley and average seasonal distribution of agricultural pumpage, 1970-81.

the growing season for the Salinas Valley is shown in figure 8 and was developed from crop-water use data by the Monterey County Flood Control and Water Conservation District (written commun., 1983). Based on this relation, estimates of annual agricultural pumpage during the 1970-81 baseline period ranged from 456,400 acre-ft/yr in water year 1969 to 558,300 acre-ft/yr in water year 1971.

Municipal

The population of Monterey County increased from 73,000 in 1940 to 316,200 in 1984; about 60 percent of the present (1982) county population resides in Salinas Valley. There also has been a trend toward urbanization. In 1950, 40 percent of the population in Monterey County lived in incorporated cities. By 1976, that percentage increased to 68 (Monterey County Planning Department, 1980).

For the previous study, Durbin and others (1978) estimated municipal pumpage by multiplying the 1970 populations of eight towns in the Salinas Valley by a constant per capita water consumption rate. Pumpage at the Fort Ord military base was not included. A recent field survey of municipal water use in the valley by the Monterey County Flood Control and Water Conservation District (1984) provided more detailed and up-to-date municipal pumpage

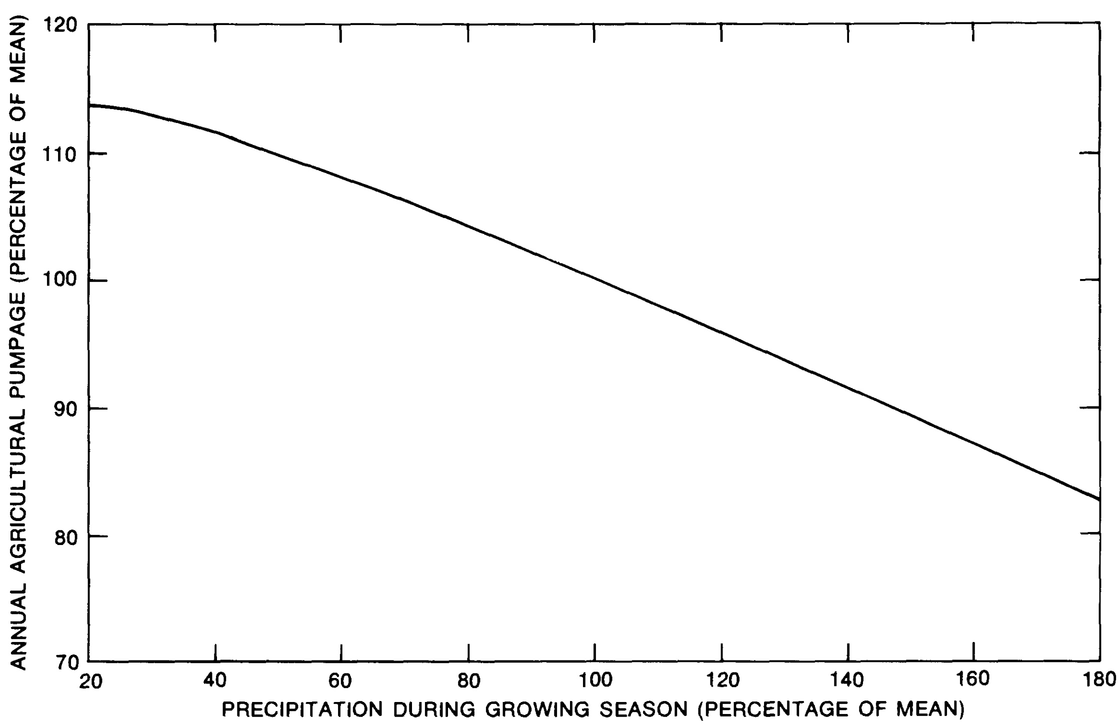


FIGURE 8. — Relation of precipitation during growing season to annual agricultural pumpage (Monterey County Flood Control and Water Conservation District, written commun., 1983).

information for the present study. Average annual municipal pumpage for 1970-81 is shown in table 1. Total pumpage for the valley, including Fort Ord, is about 700 acre-ft/yr (3 percent) more than the total estimated in the previous study. As before, municipal pumpage was assumed to occur at a constant rate throughout the year.

Evapotranspiration

Durbin and others (1978) assumed that the only loss of ground water due to evapotranspiration was from deep-rooted riparian vegetation along the Salinas River channel. This loss was estimated to be 25,000 acre-ft/yr in the study area. The same value was used in this study.

TABLE 1.--*Average annual municipal pumpage for Salinas Valley during 1970-81*

[Average population: Average of 1970 population (U.S. Bureau of Census, 1971) and 1982 population (Monterey County Flood Control and Water Conservation District, 1984)]

Community	Average population	Average pumpage (acre-ft/yr)
Castroville	3,500	717
Fort Ord	[1]29,930	5,209
Gonzales	2,840	512
Greenfield	3,620	561
King City	5,030	966
Marina	11,090	1,533
Salinas	72,360	11,795
San Ardo	480	116
Soledad	6,490	755
Spreckels	[1]670	158
Total....................	136,010	22,322

[1]Unaveraged 1982 population (Monterey County Flood and Water Conservation District, 1984).

DIGITAL SIMULATION OF THE GROUND-WATER BASIN

A digital model represents a simplified approximation of the natural system. It is limited by the degree of hydrologic understanding reflected in the equations used to describe flow processes and by the availability of accurate, spatially distributed measurements of the physical properties of the natural system. The results of model simulations must be cautiously interpreted and qualified because of the assumptions and simplifications inherent in the model and the data.

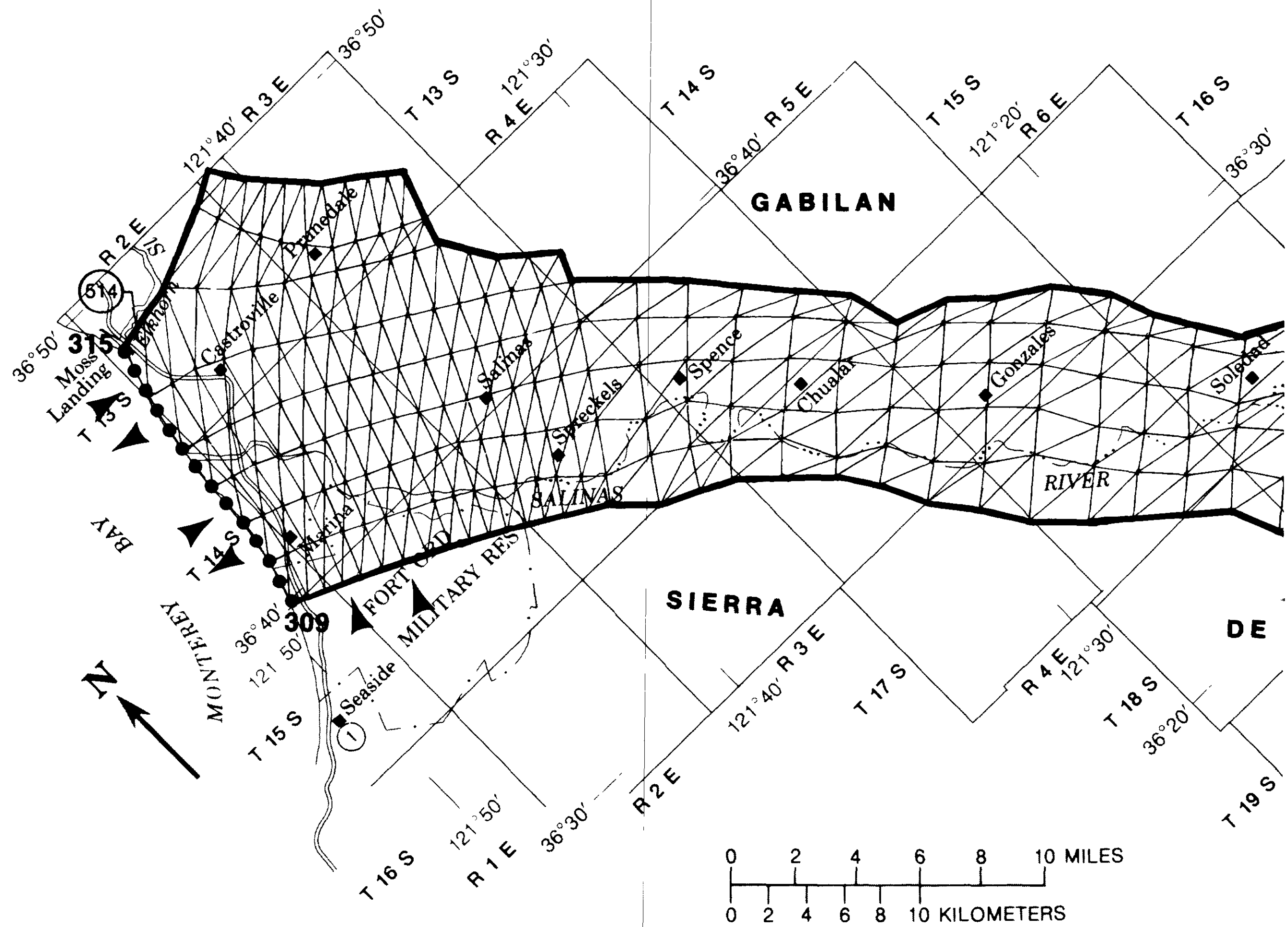
The digital model of the Salinas Valley ground-water basin solves the mathematical equation describing two-dimensional ground-water flow using the finite-element method (Hromadka and others, 1985). The model grid consists of 315 nodes and 514 triangular elements (fig. 9). The node spacing is similar to that used by Durbin and others (1978), except that the node density is doubled in the area between Gonzales and the coast.

There are two types of model simulations, and each type requires a different form of data. The first is a steady-state simulation, in which single, time-averaged values of all variables are used in the model. The model output presents an instantaneous view of basin hydrology for the mean hydrologic conditions existing during the period of averaging. Because a steady-state simulation does not involve the passage of time, transient effects due to aquifer storage changes do not occur. The storage coefficient is eliminated from the analysis. A steady-state simulation does not represent any actual point in time, but rather a long-term view of basin hydrology without seasonal or annual variations. For simulations of baseline conditions in the Salinas Valley, model input was obtained by averaging daily, monthly, or annual measurements for 1970-81.

The second type of model simulation is called a transient simulation. Transient simulation includes the seasonal and annual variations in flows and water levels. For the purpose of computation, the model divides the elapsed time into discrete intervals or steps, during which the values of all variables are assumed to remain constant. Time-step durations of 1 month were used in the Salinas Valley model. Time-varying variables in the model were assigned an input value for each time step of the simulation.

Model Assumptions

Ground-water flow in all parts of the valley was assumed to be essentially horizontal and therefore can be reasonably simulated with a two-dimensional analysis. Ground-water flow is in fact primarily horizontal in the unconfined areas of the ground-water basin. Some vertical flow does occur in the confined area, where vertical head gradients are created by the concentrated effect of pumping in the "180-foot" and "400-foot" aquifers. Vertical head differences of about 10 feet have been measured between the two aquifers.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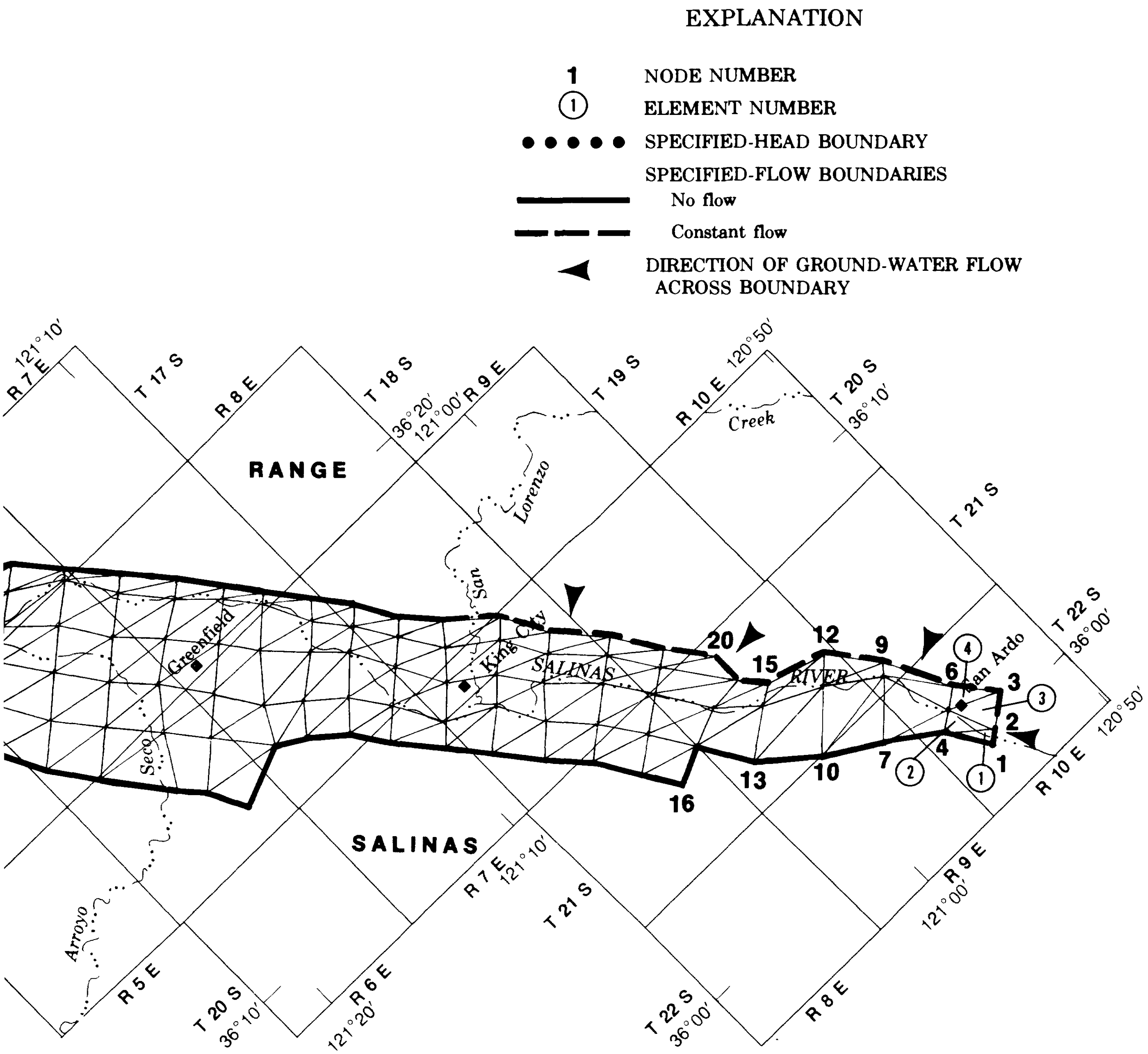


FIGURE 9. – Finite-element grid and boundaries for the ground-water model.

These vertical head differences are transient; over time they are eliminated or offset by vertical flow of water. A three-dimensional model would be better able to simulate local, transient water-level patterns in individual aquifer horizons. It was not possible to develop an accurate three-dimensional model for this study because of the lack of sufficient data describing the vertical distribution of hydraulic properties in the confined area. For the purposes of identifying basinwide flow patterns and water budgets as well as investigating the long-term effects of management alternatives, a two-dimensional model is sufficiently accurate. The two-dimensional model used in this study simulates water levels which are arithmetically averaged in the vertical dimension. Arithmetic averaging can be justified by noting that in confined ground-water systems, flow is linearly proportional to head. Several other assumptions were related to the two-dimensional analysis. Saturated flow thickness was assumed to be constant in the confined area. In unconfined areas, it was assumed to vary with the rise and decline of the water table. All wells were assumed to fully penetrate the saturated thickness of alluvial materials. Aquifer storage responses were assumed to be instantaneous.

Average basin hydrology during 1970-81 was assumed to be accurately represented using steady-state simulations. Steady-state simulation of an historical period is only valid if there were no net changes in aquifer storage during that period. Water-level hydrographs for 41 wells in Salinas Valley were analyzed for cumulative trends during 1970-81. Linear regression of the hydrographs indicated a pattern of slight water-level declines in most parts of the valley. Estimates of local storage coefficients and geographic pumpage distribution were used to convert the water-level declines into estimates of cumulative ground-water storage changes.

The average annual decrease in ground-water storage for the entire Salinas Valley during 1970-81 was about 3,400 acre-ft/yr. This number is only a rough estimate due to the small number of wells evaluated and the approximate estimates of storage coefficient and pumping area used in the calculations. However, this volume of storage change is less than 1 percent of the average annual water budget for the basin. This is a negligible amount, and any errors introduced by the assumption of steady-state conditions are consequently small.

The locations of onshore basin boundaries in the model were identical to those described earlier for the natural system. Flow across constant-flow boundaries was assumed to be evenly distributed along the lengths of those boundaries.

The northwest boundary of the modeled area coincided with the coastline. It was assumed that the offshore portions of the aquifers and their hydraulic connection with the ocean could be represented by a head-dependent boundary at the coastline. Because the submarine outcrops are not far from shore, ground-water levels at the coastline remain near sea level. Head losses associated with flow through the offshore part of the aquifers make it possible for ground-water levels at the coastline to be slightly above or below sea level. The offshore flow resistance is accounted for in the model by a leakance factor which effectively controls the amount by which water levels along the boundary can vary from sea level.

Effects on ground-water flow due to the different densities of seawater and freshwater were assumed to be negligible. An alternative approach, sometimes used in three-dimensional simulations of coastal areas (Ryder, 1985; Guswa and LeBlanc, 1985), is to correct boundary heads to account for the density difference and assume the saltwater-freshwater interface is a stationary no-flow boundary. In a comparison of the two approaches using a three-dimensional model of another basin on the California coast (E. Yates, U.S. Geological Survey, written commun., 1987), simulated boundary flows were essentially the same in both cases. Differences in simulated water levels were at most a few feet and were limited to areas near the coast. These results indicate that errors in this study due to the assumption of constant fluid density are probably small.

The Salinas River was assumed to be in hydraulic connection with ground-water at all times and along its entire length. Seepage to or from the river was assumed to be proportional to the vertical hydraulic conductivity of the riverbed, the wetted area, and the difference in hydraulic head between the river and adjacent ground water; it was assumed to be inversely proportional to riverbed thickness. In the model, riverbed conductivity and thickness were combined into a single infiltration rate coefficient, which was assumed to decrease gradually in the downstream direction. Depth and width of flow in the river were estimated from discharge using empirical power functions developed by Durbin and others (1978).

The assumption that river seepage is head-dependent was implemented in the model by calculating ground-water levels, riverflow, and seepage rates simultaneously during each simulation. Riverflow at the upstream model boundary was routed in the down-stream direction, and seepage and outflow were calculated at each successive river node. This ensured that each seepage computation reflected local water levels and that the overall mass balance for the river was maintained.

The head-dependent seepage equation used in the model is valid only as long as a direct hydraulic connection exists between the river and the nearby ground water. If the water table falls below the bottom of the riverbed, an unsaturated zone is created and seepage is no longer dependent on ground-water levels. During the simulations done for this study, computed water levels at river nodes upstream from Chualar were never more than 10 feet below the riverbed. Discrepancies of this magnitude could easily be accounted for by local ground-water mounding beneath the river, which can not be simulated in detail by a regional model with a coarse node grid. In the confined area, simulated water levels were occasionally greater than 10 feet beneath the riverbed. However, the assumption of hydraulic connection probably is still valid. The degree of confinement is great enough to create vertical-head gradients in response to pumping. The model was designed to simulate water levels in the pumping horizons, which are lower than water levels elsewhere in the vertical section. So the water table in the shallow alluvium immediately adjacent to the river could be at river level even though the piezometric water level in deeper horizons is lower. The ground-water system in the confined area is leaky enough that given sufficient time, low water levels in the deeper horizons induce seepage from the river.

Agricultural and municipal water demand were assumed to be met entirely by ground-water pumpage. Irrigation-return flow was assumed to be local and instantaneous.

Model Calibration

Procedure

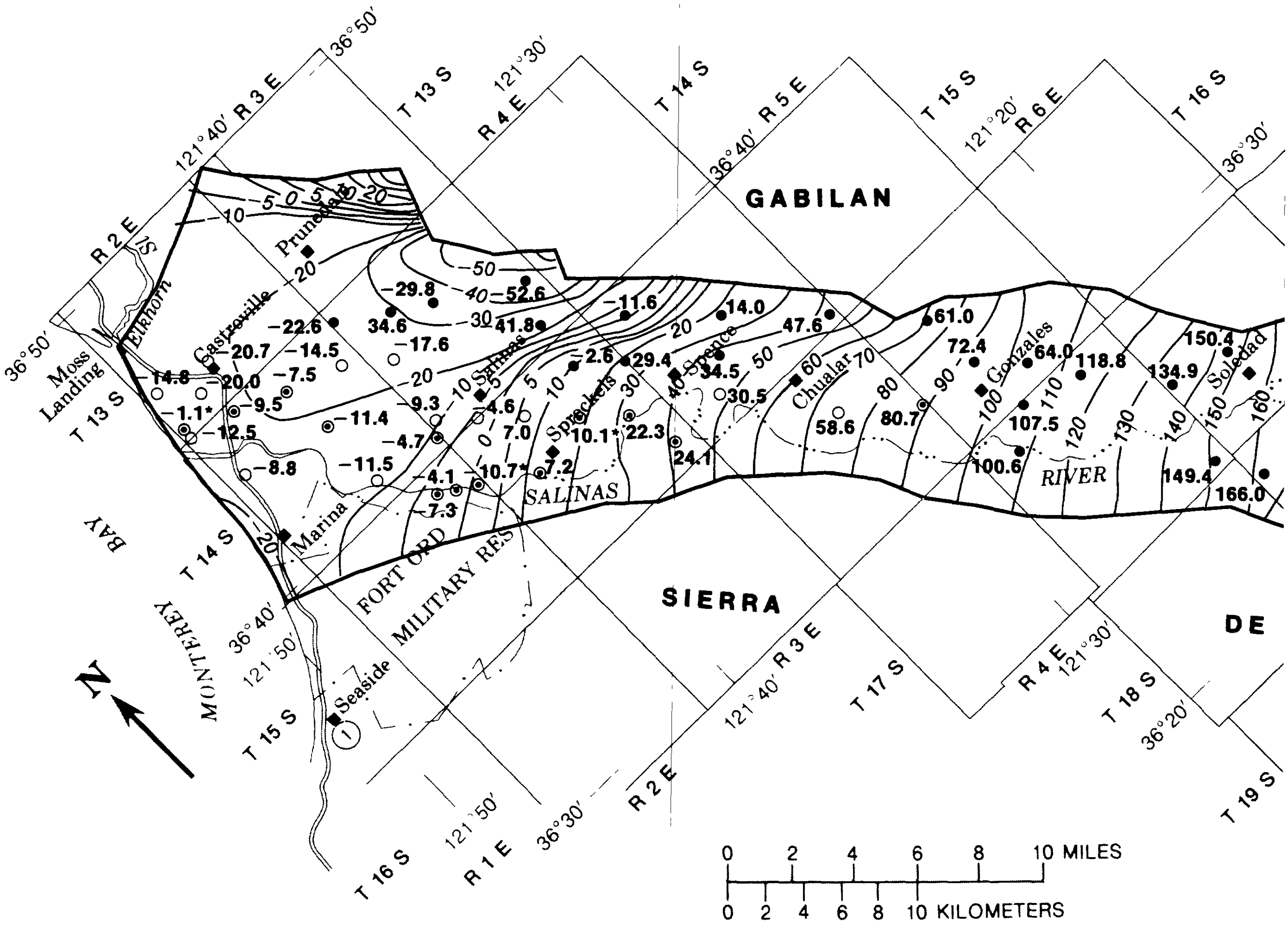
In the process of model calibration, selected input variables were manually adjusted to achieve a better match between simulated and measured basin characteristics during 1970-81. Characteristics used for comparison included ground-water levels, riverflow and seepage, and the rate of seawater intrusion. The variables adjusted during calibration were hydraulic conductivity, storage coefficient, irrigation-return flow, the head-dependent boundary leakance factor, riverbed infiltration rate coefficients, areal extent of the confined area, and ground-water inflow from the Pancho Rico Formation. For each variable, the range of adjustment was limited either to the range defined in the preceding discussion of basin geohydrology or to a range of reasonable values determined by subjective interpretation of the geologic and hydrologic properties of the basin. For example, sedimentary grain size determined from lithologic well logs were used to estimate a reasonable range of hydraulic conductivity (Lohman, 1979). Both steady-state and transient simulations were used for calibration.

For the steady-state calibration, measured water levels in 65 wells in the valley were chosen for comparison with simulated water levels. Water levels for 132 months (1970-81) were averaged from monthly water-level measurements collected by the Monterey County Flood Control and Water Conservation District. For the transient calibration, simulated and measured water levels and riverflow were compared on a monthly basis for 53 wells during 1970-81.

Results and Discussion

Simulation Errors

Simulated water levels from the steady-state calibration compare well with measured water levels as shown in figure 10. The distribution of the errors in simulated water levels is shown in figure 11, and the cumulative distribution of the errors in simulated water levels is shown in figure 12. Seventy percent of the errors are less than 9 feet and 90 percent are less than 22 feet.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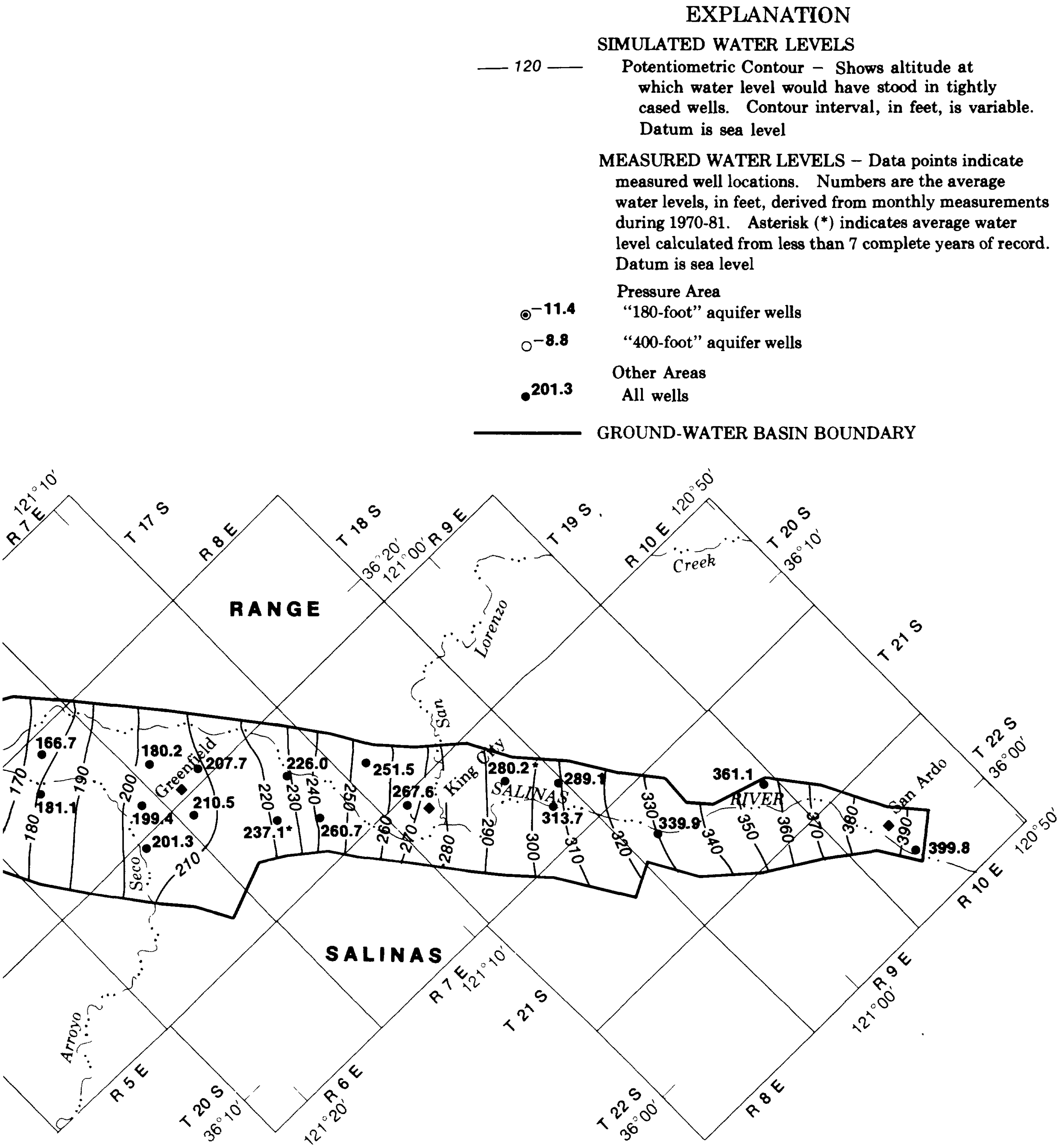


FIGURE 10. – Measured and simulated mean water levels for 1970-81.

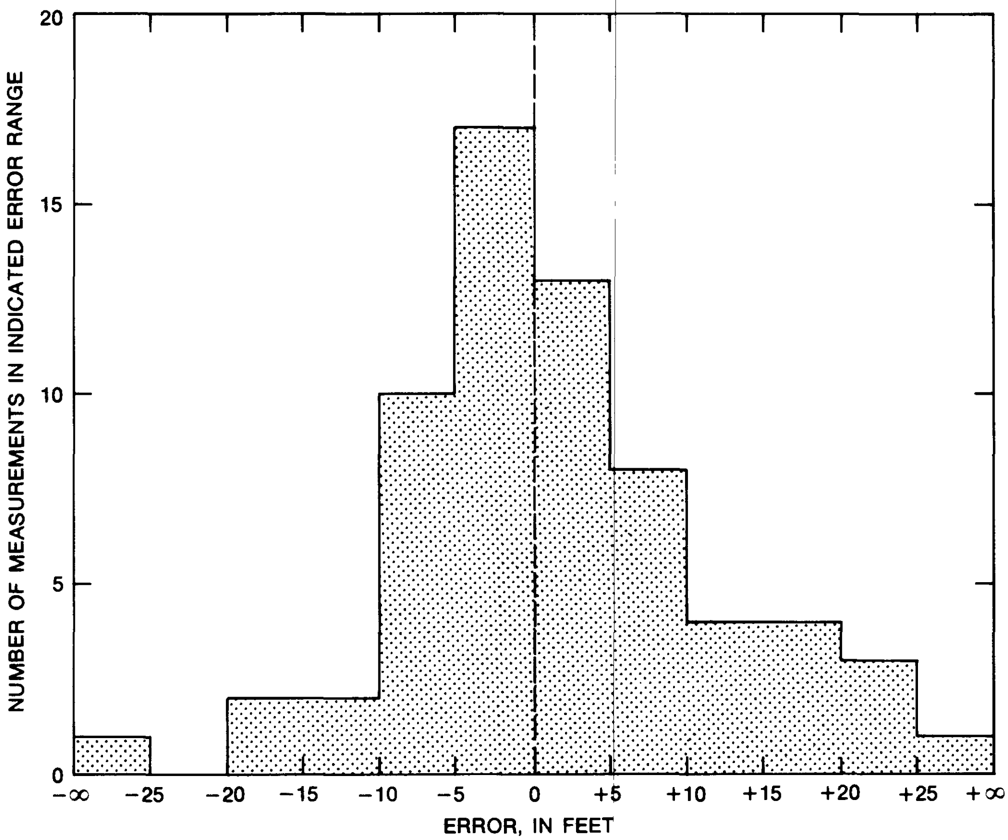


FIGURE 11. — Distribution of errors in simulated water levels at 65 wells for the steady-state calibration, 1970-81.

Spatial patterns in the water-level errors also are shown in figure 10. The measured wells are not distributed randomly or uniformly throughout the valley, which means that the error statistics emphasize model accuracy in some areas more than others. Clustering of some of the measured wells also indicates the presence of local variations in water-level measurements. For example, two wells spaced about 4,000 feet apart near Spreckels have average water levels that are different by 6.6 feet. Other wells in the area indicate that the difference attributable to regional water-level gradients would be only about 2.5 feet. Also, comparison of water levels from a group of wells north of Salinas indicates that the water level at one well is anomalous. The average measured water level at the well is 56 feet higher than the average of the average water levels at the four surrounding wells. The surrounding wells are all within 2.5 miles of the central one, and they all have average water levels within 16 feet of each other. If these patterns are not merely artifacts of measurement errors, they indicate the existence of significant small-scale spatial variability in aquifer characteristics. The model does not attempt to simulate spatial variability at this scale.

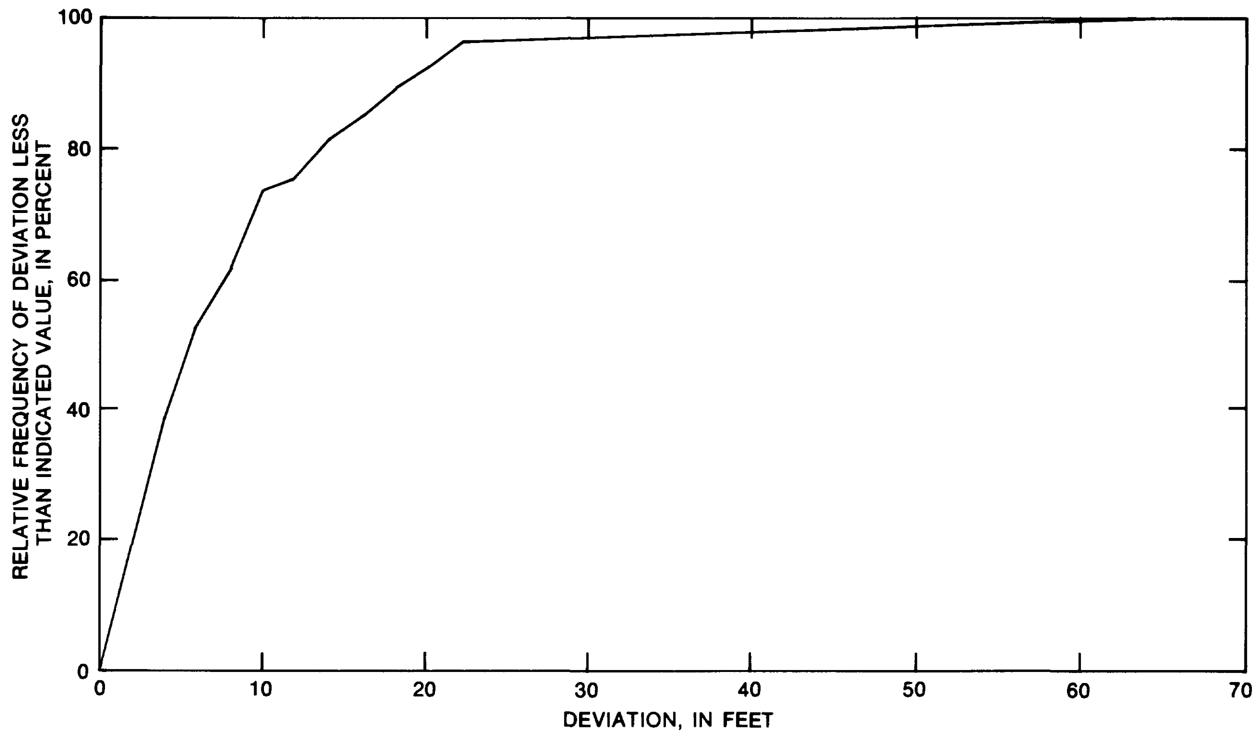


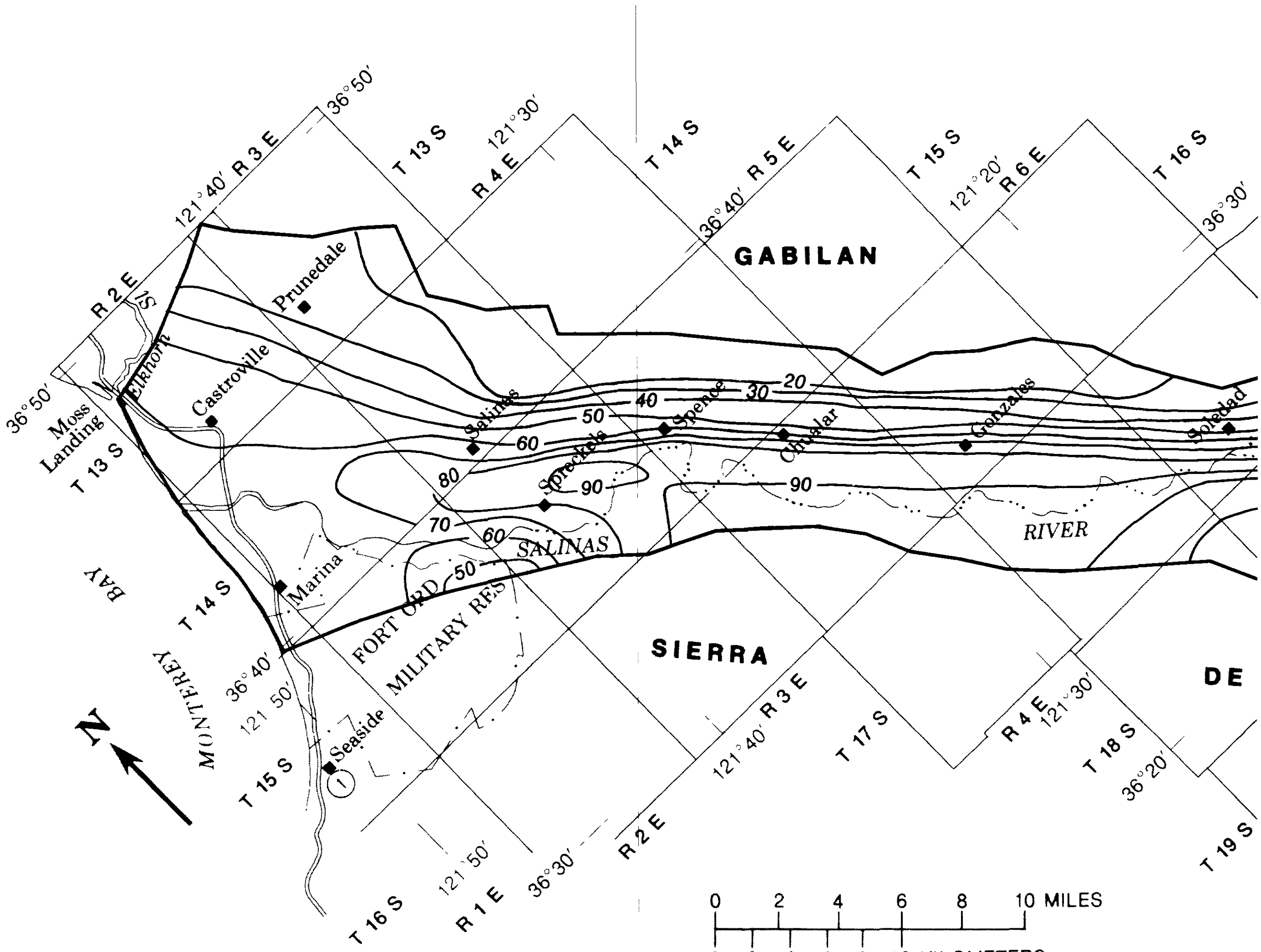
FIGURE 12. — Cumulative relative frequency of the deviation of simulated water levels from measured water levels at 65 wells for the steady-state calibration, 1970-81.

Another source of error between simulated and measured water levels occurs near the coast, where average annual water levels in the "180-foot" and "400-foot" aquifers are typically different by about 10 feet. The model can simulate only one aquifer and was calibrated to match an average of the measured water levels in the two aquifers. This calibration strategy, however, inevitably produced deviations between the measured and simulated water levels.

Aquifer Properties

The calibrated horizontal hydraulic conductivity of the alluvial deposits is shown in figure 13. The greatest change in hydraulic conductivity between the estimates by Durbin and others (1978) and the present estimates is a decrease from 170 to 90 ft/d in a small area near King City. The largest increase is from 86 to 120 ft/d near the point where the Arroyo Seco enters the valley.

The storage coefficient of the alluvial deposits is shown in figure 14. Values are indicated for 10 areas representing uniform aquifer storage properties. These areas of uniformity were delineated on the basis of similarity of hydrographs of measured water levels.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EXPLANATION

— 110 — LINE OF EQUAL HYDRAULIC CONDUCTIVITY – Interval is 10 feet per day

——— GROUND-WATER BASIN BOUNDARY

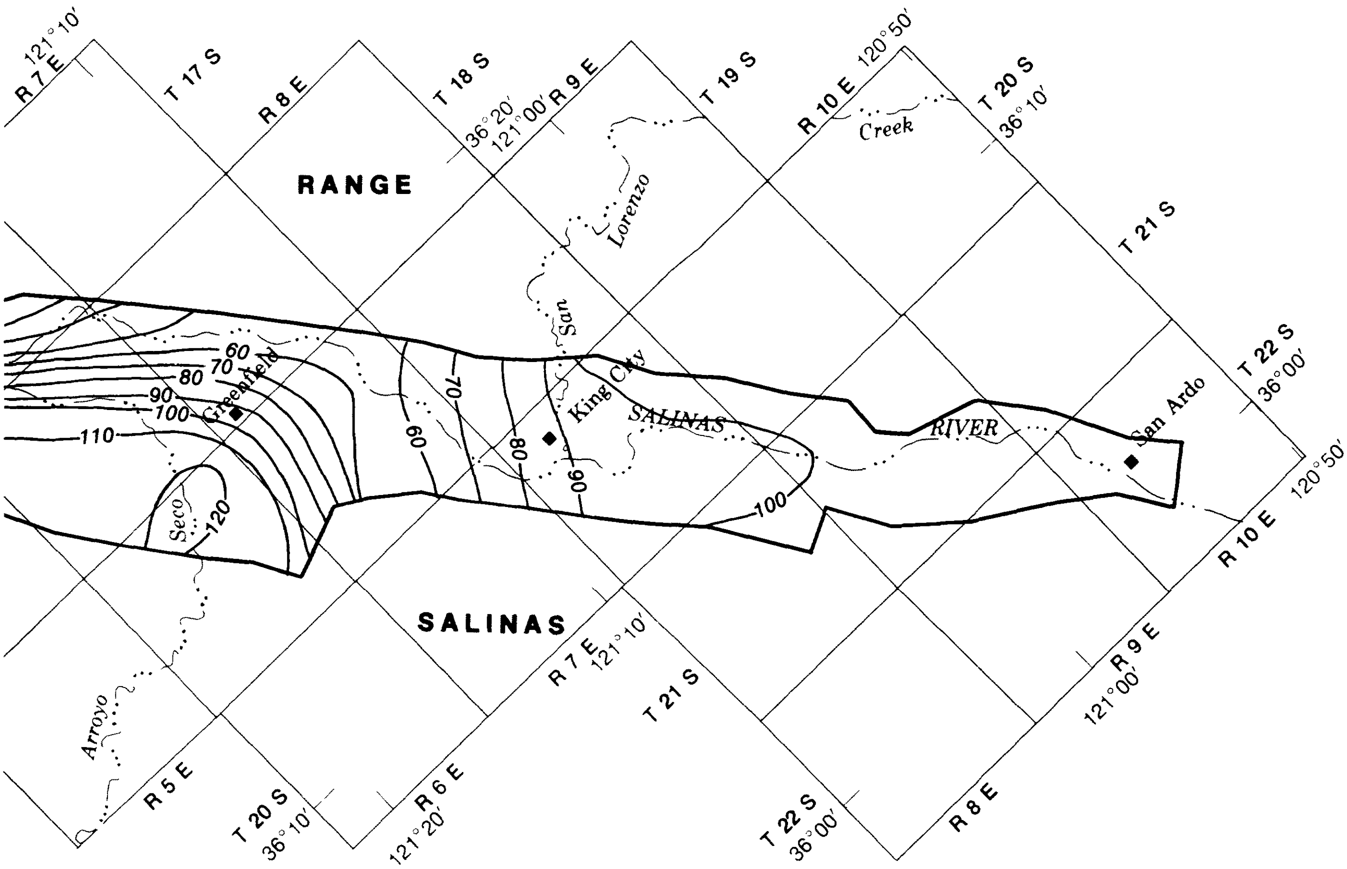
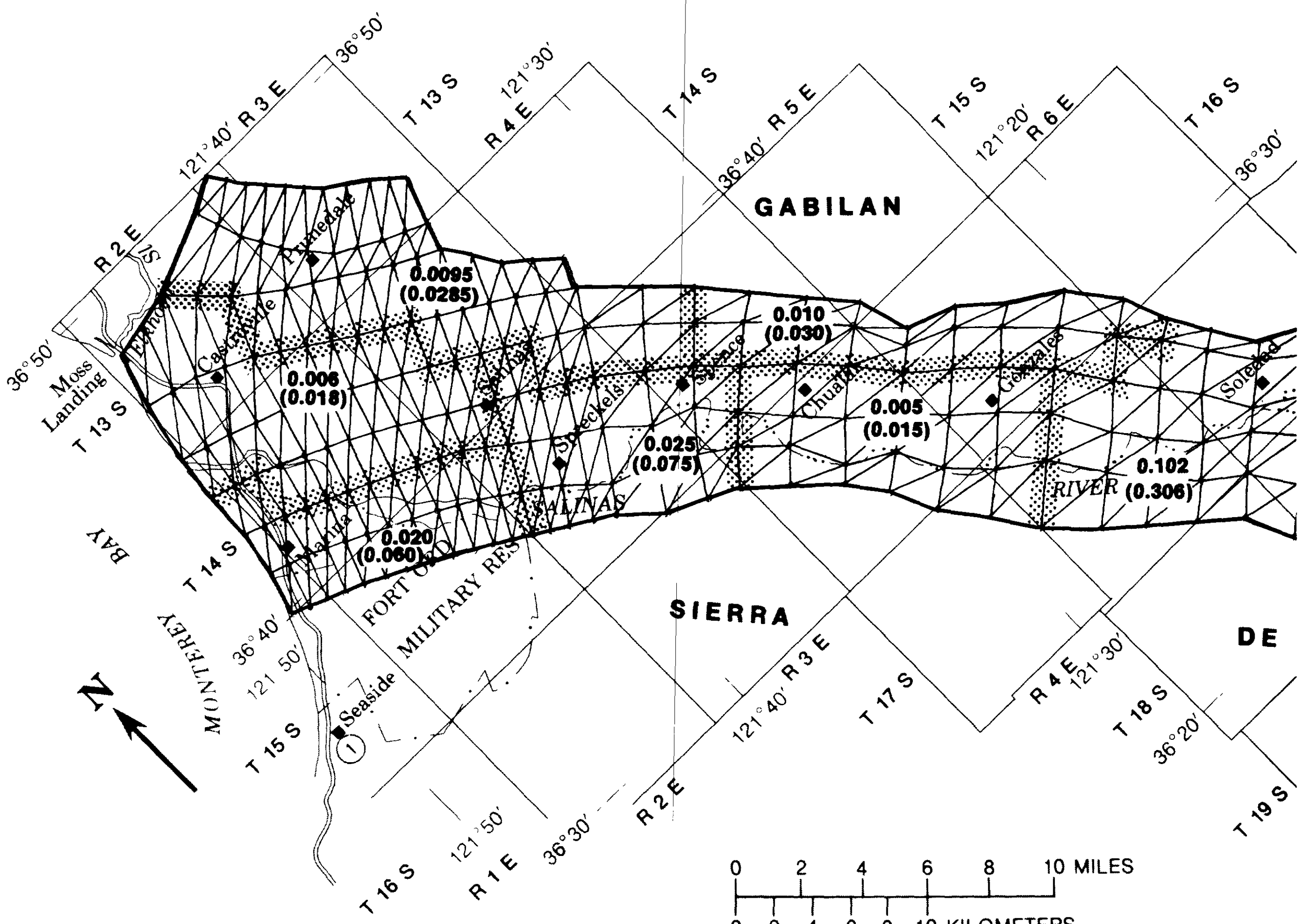


FIGURE 13. — Calibrated hydraulic conductivity.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EXPLANATION

STORAGE COEFFICIENT FOR WATER-LEVEL FLUCTUATIONS – Dimensionless

0.025	Short-term
(0.075)	Long-term
(stippled pattern)	BOUNDARY OF AQUIFER STORAGE COEFFICIENT ZONE
(solid line)	GROUND-WATER BASIN BOUNDARY

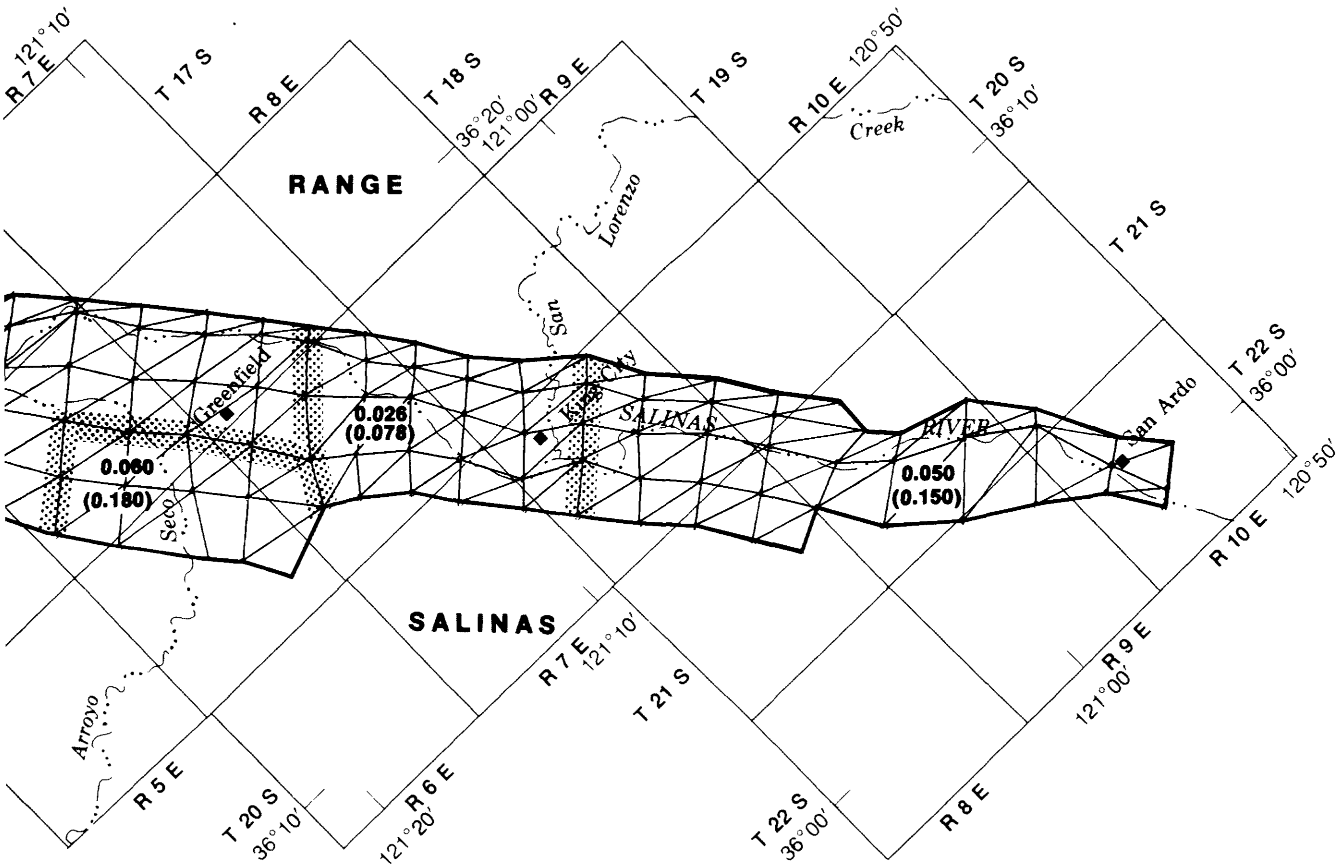


FIGURE 14. – Zones of uniform calibrated storage coefficients.

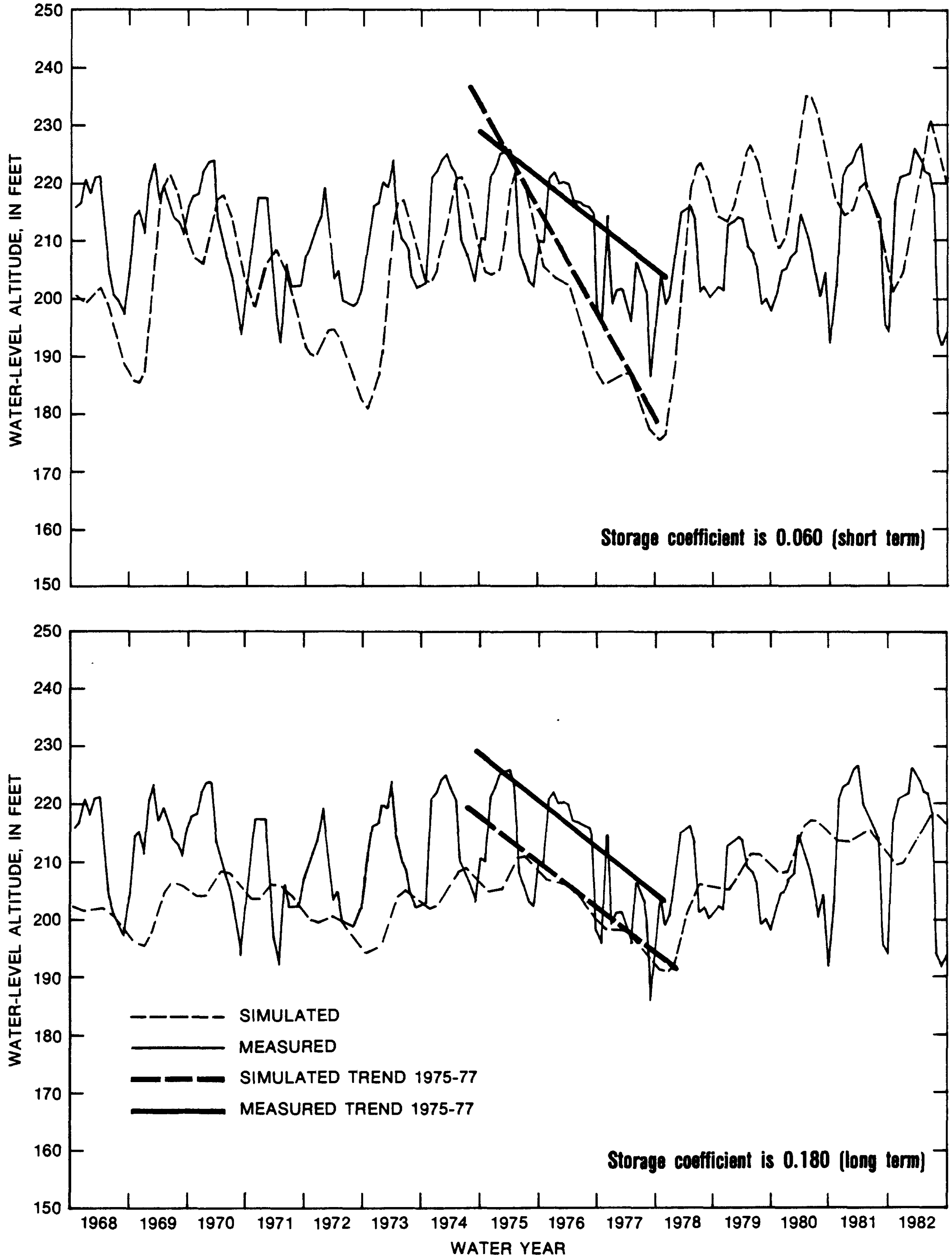
Results from the transient calibration procedure indicated that the aquifer exhibited different amounts of storage response to short- and long-term water-level changes. This phenomenon also was noticed by Durbin and others (1978) for 1944-70. Short-term annual changes in measured water levels result from seasonal cycles of summer pumping and winter recharge. Long-term water-level changes are those associated with prolonged dry periods, such as the 1976-77 drought. Compared to the long-term changes, the short-term water-level changes were large, which indicates a small storage coefficient. This is illustrated graphically in figure 15, which compares the results of two simulations, one using short-term storage coefficients and the other using long-term coefficients. The two sets of coefficients were different by a factor of three.

A plausible physical explanation exists for the apparent time-dependence of the storage coefficient. When an aquifer is stressed by pumping, a state of disequilibrium is created. The response to the stress can occur over an extended period of time and can persist even after the pumping ceases. Several factors contribute to this delay of the aquifer storage response. Because the screened interval of most wells spans only a small percentage of the total aquifer thickness, water released from storage above and below the screened interval flows an extra vertical distance to the well screen. In addition, the low vertical hydraulic conductivity retards the vertical flow of water released from storage and thus, further delays its arrival at the well.

Salinas River

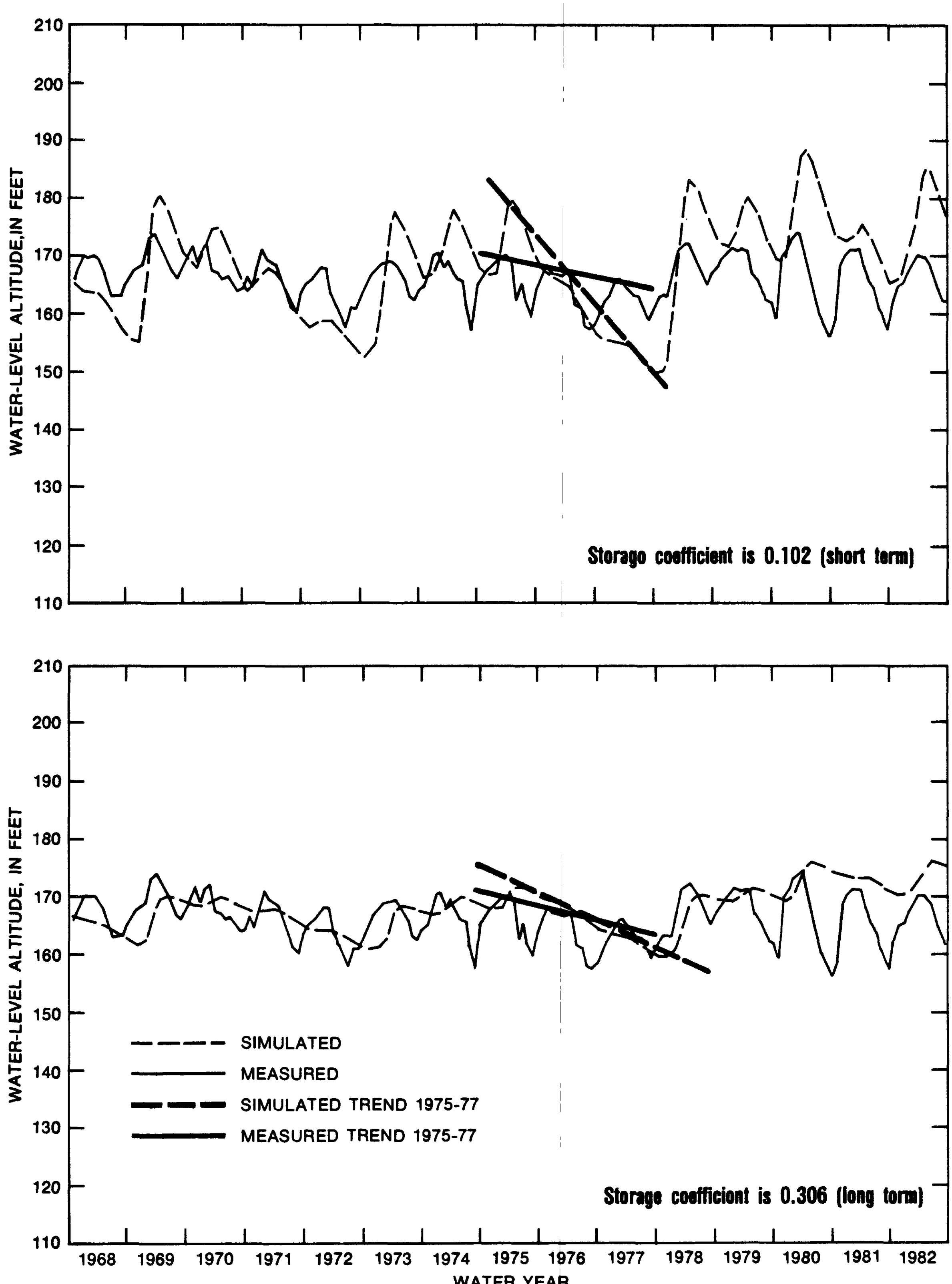
Accurate simulation of riverflows was an additional constraint on the selection of values for certain variables in the model. During calibration, simulated and measured monthly flow data were compared for two gaging stations on the Salinas River for 1970-81. These stations were Salinas River at Soledad (1968-78 only) and Salinas River near Spreckels (fig. 1). Simulated riverflows fluctuated more than the measured flows in virtually every calibration simulation. The simulated peak flows were too high and the simulated minimum flows were too low. The calibration process matched average annual flows. Simulated and measured flows at the two gaging stations on the Salinas River are shown in figure 16.

The discrepancy between measured and simulated riverflow probably results from the assumption that interaction between the river and the aquifer is instantaneous. In the simulations, summer pumpage tended to induce too much seepage from the river, causing unrealistically small simulated riverflow. Simulated winter flow was too large because winter pumpage was too small to significantly affect it. In reality, the effects of summer pumpage on seepage are delayed into fall and winter. Similarly, the effects of winter seepage extend into spring and summer. Possible reasons for these delays include temporary storage of water in riverbanks, perched aquifers, and the vadose zone. The time required for the vertical flow of water from the river to the pumping horizon also could contribute to the delays.



WELL 19S/7E-8D1 (MODEL NODE 69)

FIGURE 15. — Comparison of measured and simulated water levels at four wells using two different storage coefficients, 1968-82.



WELL 18S/6E-6M1 (MODEL NODE 92)

FIGURE 15. — Comparison of measured and simulated water levels at four wells using two different storage coefficients, 1968-82 -- Continued.

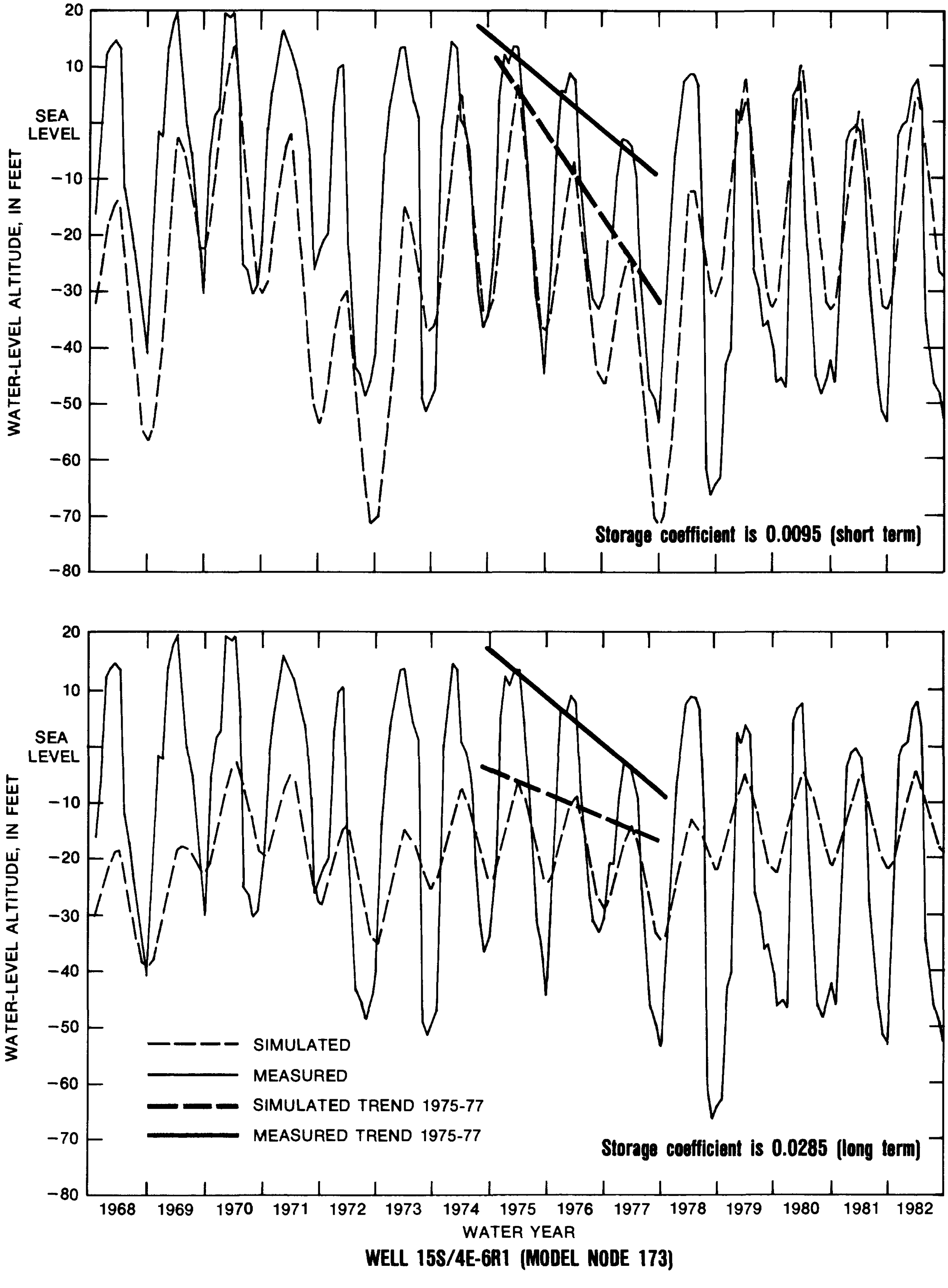
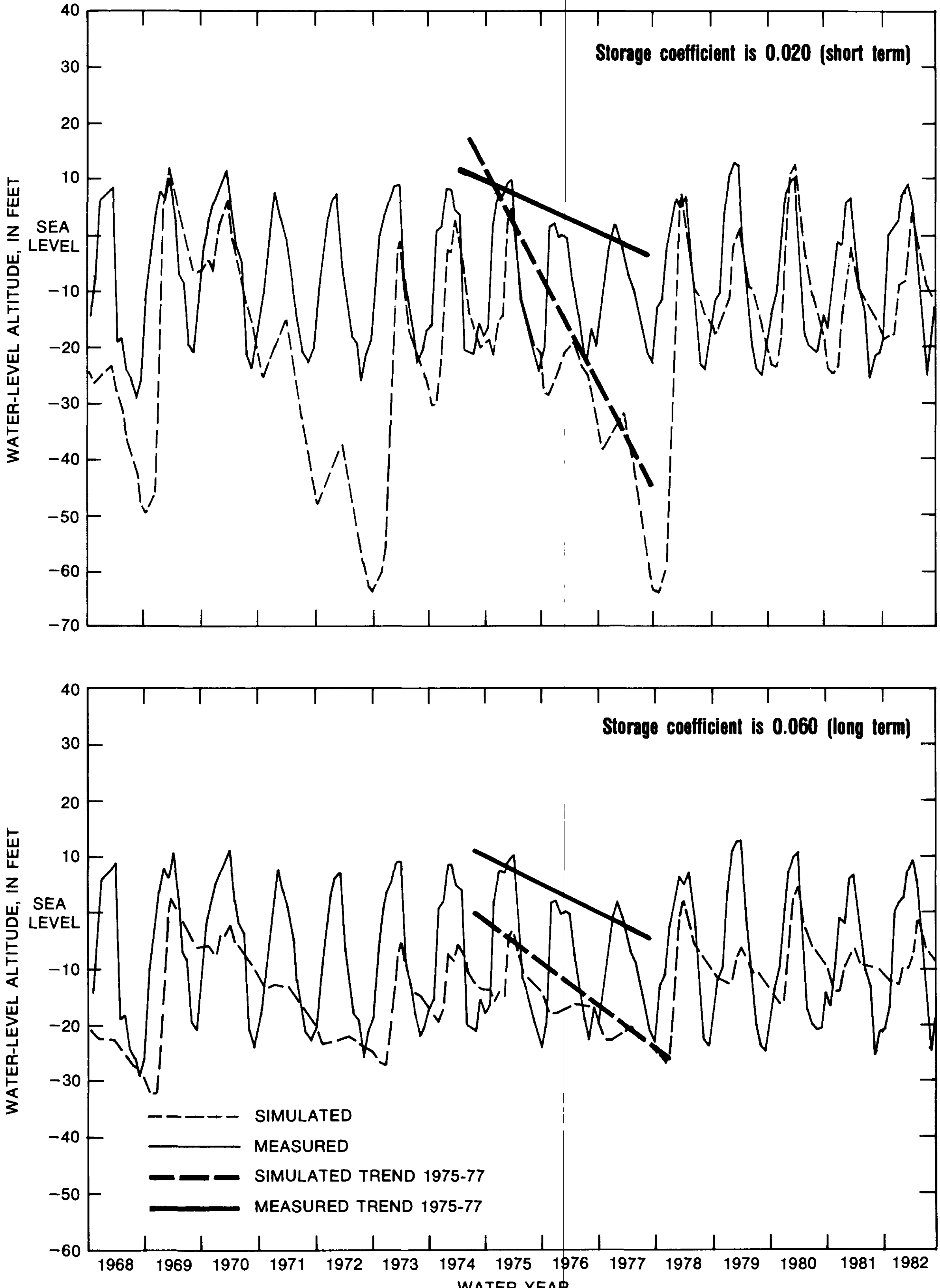


FIGURE 15. — Comparison of measured and simulated water levels at four wells using two different storage coefficients, 1968-82 -- Continued.



WELL 15S/2E-2J1 (MODEL NODE 231)

FIGURE 15. — Comparison of measured and simulated water levels at four wells using two different storage coefficients, 1968-82 -- Continued.

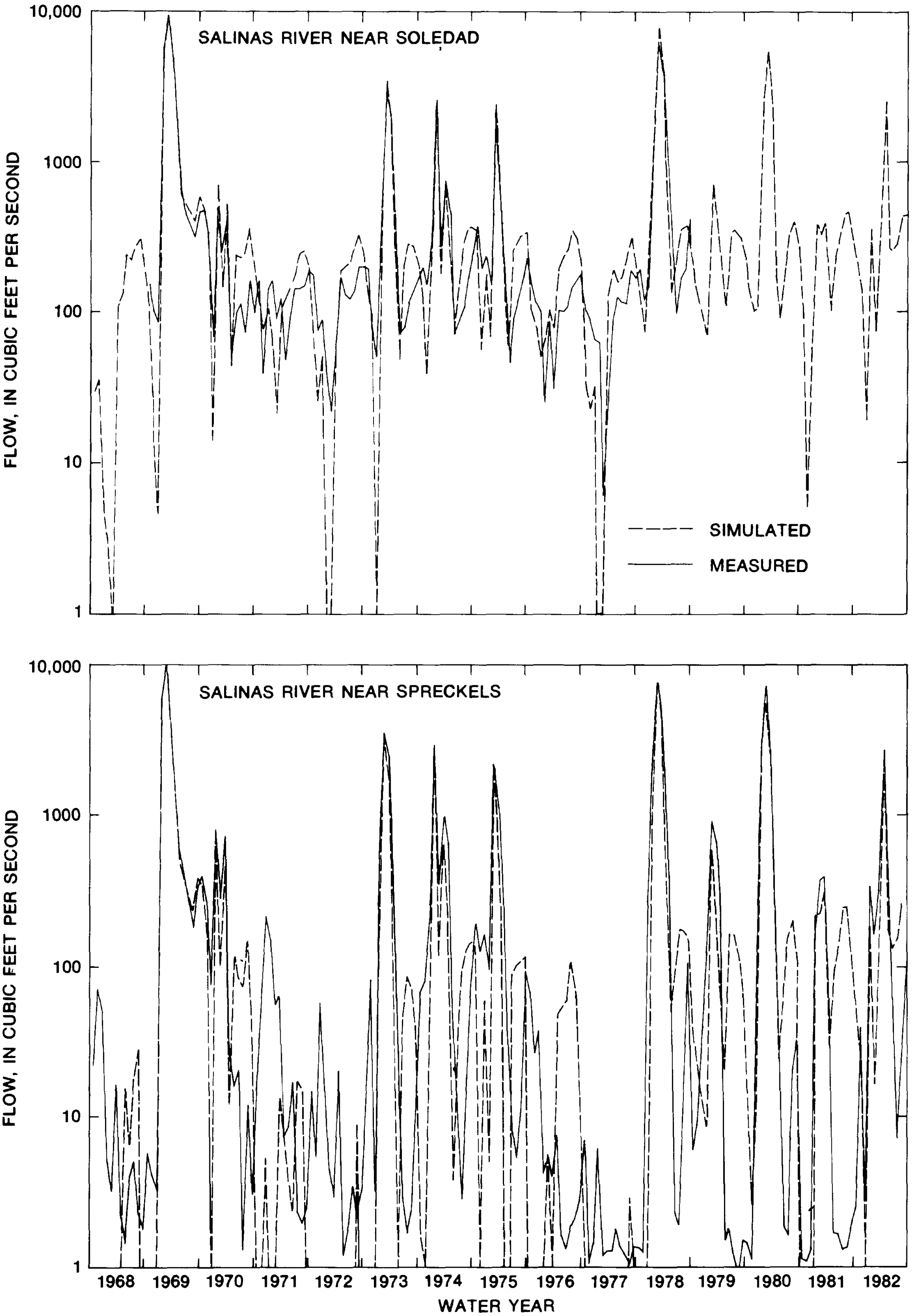


FIGURE 16. — Comparison of measured and simulated monthly mean flow for the Salinas River near Soledad and near Spreckels, 1968-82 (measured data for 1968-78 only).

Confined Area

Simulation of the confined part of the Pressure Area was a difficult aspect of the model to calibrate. Simulation of this area was affected by irrigation-return flow, riverbed infiltration rate coefficients, areal extent of confined area, the head-dependent boundary leakance factor, hydraulic conductivity, evapotranspiration of riparian phreatophytes, and aquifer thickness. All but the last two of these variables were adjusted during calibration. The difficulty in calibration lay in finding values of the variables which were simultaneously reasonable and mutually consistent and which produced accurate results.

During initial calibration simulations, the input values for the variables affecting confinement were set to reflect a commonly accepted conceptual model of the hydrogeology in the Pressure Area which assumes that a thick, continuous, confining layer extends throughout the entire Pressure Area (see fig. 2) and that there is no local irrigation-return flow, river seepage, or precipitation recharge. The resulting simulated water levels were as much as 100 feet below the measured levels, and the calculated rate of seawater intrusion was 70,300 acre-ft/yr, or about four to six times the rate estimated from measured field data (Leedshill-Herkenhoff, 1984).

In order to reasonably simulate the measured water levels and the estimated rate of seawater intrusion for 1970-81, it was necessary to increase recharge from irrigation-return flow and the Salinas River, decrease the area of confinement, and increase hydraulic conductivity in the Pressure Area. The calibrated irrigation-return flow was 26 percent of the gross pumpage in the confined area. Riverbed infiltration-rate coefficients were about 0.020 (ft/d)/ft. They were still much lower than coefficients farther upstream and reflect the effect of confinement on river seepage. Finally, the leakance factor for the coastal head-dependent flow boundary was calibrated to a value of 0.4 (ft/d)/ft.

Unconfined Area

Irrigation-return flow in unconfined areas was calibrated to 40 percent of gross pumpage. Riverbed infiltration-rate coefficients decreased gradually from 0.338 (ft/d)/ft at San Ardo to 0.113 (ft/d)/ft at Chualar. For comparison, the coefficients used by Durbin and others (1978) decreased from 0.2340 (ft/d)/ft at San Ardo to 0.0467 (ft/d)/ft at Spreckels. Ground-water inflow from the Pancho Rico Formation was chosen on the basis of simulated water levels near the inflow boundary. The calibrated value was 11,000 acre-ft/yr.

Ground-Water Budget

The estimated mean annual water budget for the Salinas Valley was determined in part by model calibration and is shown in table 2. The indicated flows represent mean annual flows under conditions which existed in the basin during 1970-81. River recharge was 58,800 acre-ft/yr greater than in the previous study. The increase was caused by recalibrating the riverbed infiltration rate coefficient, changing the baseline period used to determine mean annual inflow, and increasing the estimated mean annual pumpage. The amount of irrigation water that percolates to the water table was calculated by applying the return flow percentage to the gross pumpage. Adding 26 percent of the pumpage in the confined area (27,000 acre-ft/yr) to 40 percent of the pumpage in unconfined areas (163,300 acre-ft/yr) yields a total irrigation-return flow of 190,300 acre-ft/yr.

TABLE 2.--*Estimated mean annual water budget for the Salinas Valley ground-water basin, 1970-81*

[Numbers are rounded to nearest 100 acre-ft/yr]

Budget item	Rate of inflow or outflow	
	Acre-ft/yr	Percentage of total
Inflow		
Recharge from the Salinas River	214,300	38.3
Recharge from the Arroyo Seco	93,600	16.7
Recharge from small streams	23,300	4.2
Ground-water inflow	13,000	2.3
Percolation of irrigation water	190,300	34.0
Recharge from precipitation	6,100	1.1
Seawater intrusion	18,900	3.4
Total inflow	559,500	100.0
Outflow		
Agricultural pumpage	512,200	91.5
Municipal pumpage	22,300	4.0
Riparian phreatophyte evapotranspiration	25,000	4.5
Total outflow	559,500	100.0

The amount of seawater intrusion shown in table 2 is 7,900 acre-ft/yr greater than the amount calculated by the previous model. The increase resulted from using a larger estimate of mean annual agricultural pumpage, recalibrating hydraulic conductivity and the leakance factor for the head-dependent boundary, and including municipal pumpage for Fort Ord.

Model Reliability

Sensitivity Analysis

Because of the complexities inherent in ground-water models, a quantitative estimate of the accuracy of the results cannot be calculated directly from the separate uncertainties of the input data. Furthermore, the uncertainties of some of the input variables are difficult to estimate, especially those obtained primarily by calibration. A practical approach to assessing the stability of model results is to conduct a sensitivity analysis. In this procedure, individual input variables are systematically altered, one at a time, and an observation is made of the resulting changes in the output. These tests indicate which variables have particularly significant effects on the model results.

Results of a series of sensitivity tests using steady-state simulations are shown in table 3. Each test was based on a comparison of two simulations, which were identical except for the indicated change in one of the variables. Not all tests used identical reference simulations, but in all cases the overall set of model inputs was generally similar to that used in the final calibration.

The simulated water levels and river seepages in the Upper Valley Area were not sensitive to any of the test variables. The relative proximity of all wells in the Upper Valley Area to the Salinas River, and the year-round availability of recharge from the river probably contributed to the stability of water levels in that area. Simulated water levels in the Forebay and East Side Areas, and to an even greater extent in the Pressure Area, were more sensitive to input variations.

Changes in the infiltration rate coefficients along the Salinas River generated large changes in river seepage only when they were the limiting factor in the seepage process. This situation exists in the Pressure Area, where large pumping deficits and low water levels would ordinarily cause a high rate of seepage. In one sensitivity test using steady-state simulations,

TABLE 3.--*Results of the sensitivity analysis of the calibrated steady-state simulation, 1970-81*

Inflow/Outflow Variable	Stimulus		Response				
			River seepage		Seawater intrusion		Water levels
	Amount	Percent	Acre-feet per year	Percent	Acre-feet per year	Percent	
Riverbed infiltration coefficient[1]	+0.2 (ft/d)/ft	variable +90 to +500	+1,400	+0.7	-1,400	-7.4	+10 ft in central Pressure Area and East Side trough. Uneven distribution.
Hydraulic conductivity[2]	Variable +1 to +12 ft/d	+10.0	+730	+.3	-747	-4.2	+3 to +10 ft along Salinas River downstream of Spence and in East Side trough. -2 to -5 ft along Arroyo Seco.
Irrigation-return fraction (unconfined areas)	-0.06	-15.0	+23,195	+10.8	+1,117	+6.2	-1 to -2 ft along Salinas River downstream of Spreckels. -2 to -10 ft in East Side trough, and -1 to -2 ft in Forebay Area.
Irrigation-return fraction (confined areas)	-0.06	-23.0	+4,760	+2.2	+1,671	+9.3	-2 to -3 ft along Salinas River downstream of Spreckels. -2 to -5 ft between Castroville and Salinas.
Constant-head leakance factor	+0.1	+20.0	-768	-.4	+768	+4.3	+1 to +3 ft with 6 mi of coast.
Area of confinement[3]	-27.0 mi²	-36.0	-3,665	-1.7	-271	-1.5	+1 to +2 ft in unconfined area.
Salinas River inflow	+24,100 acre-ft/yr	+6.6	+320	+.15	-314	-1.7	Negligible change.

[1]Infiltration-rate coefficients were increased by the quantity 0.2 (ft/d)/ft between Bradley and Spence.
[2]Hydraulic-conductivity values throughout the valley were multiplied by the same factor.
[3]The boundary of the confined area was withdrawn 1 to 2 mi near Marina and Salinas, and 2 to 3 mi near Spence.

all of the coefficients upstream of Spence (fig. 2) were increased by a uniform amount, which corresponded to increases in nodal values ranging from 90 to 500 percent. As a result, total seepage from the river increased by only 0.7 percent. With the possible exception of the Pressure Area, simulated water levels in the valley were not appreciably affected by uncertainties in the riverbed infiltration rate coefficients.

Increasing the hydraulic conductivity values by a uniform factor throughout the valley generally caused slight increases in river seepage and water levels. These results occurred in nearly all parts of the valley, although the Pressure and East Side Areas were more noticeably affected. The increased water levels near the coast caused a decrease in the rate of seawater intrusion.

Of all the variables tested, irrigation-return flow had the largest effect on the model results. Adjustments in the irrigation-return flow are equivalent to adjustments in the net amount of agricultural pumpage. Because agricultural pumpage involves large quantities of water, a small change in the return-flow percentage has a major effect on model results. To illustrate this, note that the entire volume of seawater intrusion entering the basin each year amounts to only 4 percent of the gross agricultural pumpage (table 2). Because the model always calculates a balanced water budget, any changes in pumpage are automatically compensated for by changes in seawater intrusion and river seepage. For example, a decrease in the return-flow percentage for unconfined areas from 40 to 34 resulted in an 11-percent increase in river seepage and a 6-percent increase in seawater intrusion. The effect of decreasing irrigation-return flow in the confined area was similar to that in unconfined areas; but because of the coastal location of the confined area, the effect on intrusion was greater and the effect on river seepage was less.

Changes in the boundaries of the confining layer in the Pressure Area had a slight effect on model results. For example, decreasing the lateral extent of confinement near Marina, Spence, and the East Side Area (a decrease of 36 percent of total area of confinement) caused changes of less than 2 percent in seepage and intrusion.

Increasing the leakance factor for the head-dependent boundary along the coast caused an elevation of water levels near the coast and an increase in the rate of seawater intrusion. In one sensitivity test, the effect of increasing the factor from 0.4 to 0.5 was an increase in seawater intrusion of 9.3 percent and increases of 1 to 3 feet in water levels in areas within about 6 miles of the coast.

The model was not sensitive to the quantity of flow in the Salinas River except when the simulated flow decreased to zero. An increase in the river inflow at Bradley of 24,100 acre-ft/yr (6.6 percent) resulted in an increase in total river seepage of only 320 acre-ft/yr (0.15 percent). When flow in the downstream reaches of the river ceased entirely, as occurred in transient simulations with large quantities of pumpage, the primary source of recharge for the coastal area was effectively eliminated. This caused unrealistically low simulated water levels in the summer. When the dry condition was prolonged for several consecutive years, an unrealistically steep long-term decline in simulated water levels resulted.

The simulated rate of seepage from the river is most sensitive to the pumping demand. Seepage rates could be increased by 11 percent simply by decreasing the irrigation-return flow in unconfined areas from 40 to 34 percent.

The simulated rate of seawater intrusion was fairly stable for a variety of conditions. Its value was between 16,000 and 20,000 acre-ft/yr in almost all of the calibration and sensitivity simulations.

Model Limitations

Ground-water models are simplified representations of complex natural systems. Because of these inherent simplifications, models cannot exactly simulate every detail of the natural systems. For this reason, caution is always necessary when formulating and interpreting model simulations. It is usually the case that different levels of confidence can be placed in different aspects of model performance. Assessing the relative merits of different parts of a model requires familiarity with the assumptions and data used during the development of the model and with the sensitivity of the model output to changes in the input variables. Identification of model limitations is necessary to prevent gross misapplication of a model or misinterpretation of its results.

Several limitations of the Salinas model result from its two-dimensional representation of the ground-water basin. The absence of vertical ground-water flow and related storage effects limits the ability of the model to simulate local variations in flows and water levels. These problems primarily affect transient simulations, and may have caused the unsatisfactory simulations of the summer pumping depression near Castroville and the water-level trough that would be created by an extraction-type seawater intrusion barrier. Delayed yield or other storage effects not simulated by the model also may partially explain the inability to simulate local pumping troughs.

Other drawbacks to the two-dimensional analysis result from the assumptions that the alluvial deposits consist of a single homogeneous aquifer and that wells are fully penetrating. In reality, pumping and water levels in areas such as the Pressure Area are measured from thin individual aquifers in the alluvium. The effects of a given pumping stress on a thin aquifer are much greater than they would be on a thick aquifer. For steady-state simulations, it is possible to compensate for the difference between the simulated and actual aquifer thicknesses by adjusting the hydraulic conductivity. But it remains difficult to simulate the seasonal water-level changes measured in any given aquifer layer. In unconfined areas, the fact that wells penetrate only a small part of the total alluvial thickness causes the measured water levels to fluctuate differently than they would if the wells were fully penetrating.

The node spacing in the model, which ranges from 0.7 to 2.5 miles, also limits the ability of the model to simulate localized water-level drawdowns. Even if the node density were increased, the lack of data to define the detailed spatial distribution of the aquifer properties would prevent good simulation of water levels at every point in the basin. The well logs and water-level measurements that are available indicate large spatial variability of aquifer properties, but the lack of sufficient data rules out the possibility of systematically including the spatial variability in the model. For this reason, the model should only be applied to regional problems that include areas of at least several tens of square miles.

The model can use only one set of nodal storage coefficients during a simulation. The appropriate set must be selected according to the purpose of the simulation. Short-term coefficients must be used for simulations of seasonal water-level changes. Long-term coefficients must be used for simulations of extended wet or dry periods or of long-term changes in the pumping regime.

Several factors limit the ability of the model to accurately simulate flow in the Salinas River. The actual spatial distribution of riverbed infiltration rate coefficients along the river is unknown. Furthermore, the model does not account for delays in the interaction between ground-water pumping and river seepage. Also, tributary inflow is assumed to occur at only two locations, rather than at the numerous points of inflow that actually exist along the length of the river. For these reasons, the model should not be used for precise simulation of Salinas River flow. However, because the rate of seepage from the river is not generally sensitive to variations in river discharge, the accuracy of the seepage estimate is greater than that of the riverflow itself. The model assumes a continuous hydraulic connection exists between the Salinas River and nearby ground water. An interruption of riverflow or a prolonged extreme drought could create a zone of unsaturation beneath the river, which would violate the assumption. In simulations of such conditions, the model will tend to overestimate river recharge.

In transient simulations, a long period may be required for the modeled system to fully adjust to a change in the hydrologic regime. For example, if a series of identical years were simulated, one would expect the model to produce identical simulated water levels for the corresponding months of each year. In practice, it was found that even with reasonable initial conditions, about 4 to 6 years elapsed before simulated water levels were consistently within 0.1 foot of those for the same month of the preceding year. Large or sudden changes in hydrologic regime can require even longer periods for complete reequilibration. In one simulation, eight identical drought years were introduced after a series of identical years of baseline conditions. At the end of the eighth drought year, long-term water-level trends were still declining, although not as rapidly as during the first several years. The long reequilibration period does not affect steady-state model simulations. But for transient simulations of management alternatives, the duration of the simulation needs to be long enough to allow full readjustment of the modeled system.

The model cannot predict the location of the interface between saline and fresh ground water because it does not account for hydraulic effects caused by the salinity of seawater. In general, however, a decrease in or reversal of outflow to the ocean will result in landward displacement of the interface.

In spite of the aforementioned limitations, the model is the best available tool for comprehensively analyzing all hydrologic processes in the Salinas Valley ground-water basin. The model incorporates all available data for the system and uses scientifically verified algorithms to calculate quantitative estimates of flows and water levels including their spatial and temporal variations. The model also has the ability to simulate historical and hypothetical hydrologic conditions. This dual capability allows for verification of model accuracy as well as simulation of the effects of potential water-resource management alternatives.

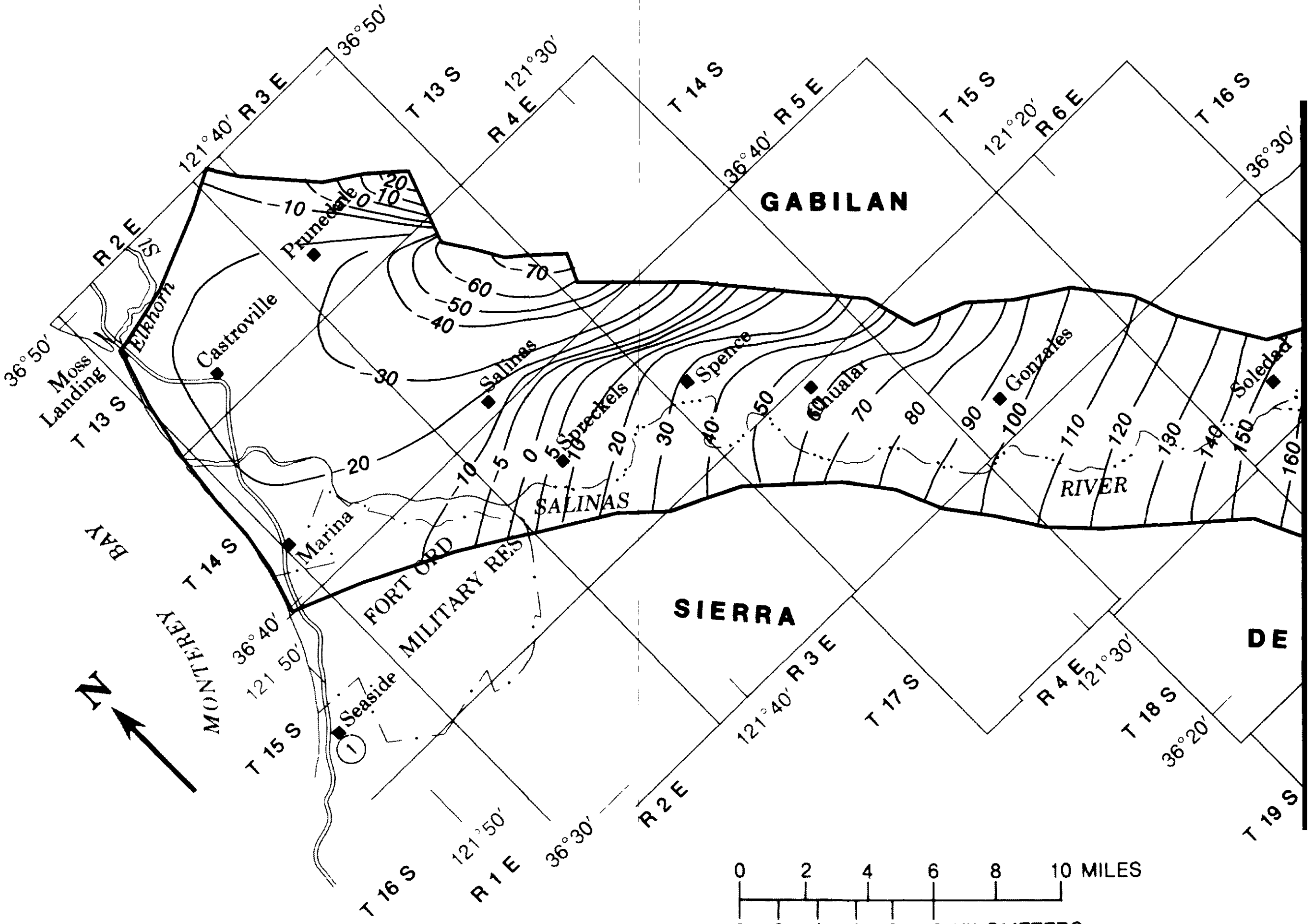
SIMULATION OF MANAGEMENT ALTERNATIVES

The most urgent issue in water-resources management in the Salinas Valley is the problem of seawater intrusion. The goal of management is to supply fresh, uncontaminated water to the cities and farms near the coast, and to accomplish this at a reasonable cost without adversely affecting the quantity or quality of water available in other parts of the valley. Several management alternatives were simulated using the model. The alternatives included inaction, which was assumed to lead to continued increases in pumpage with time; pumpage decrease; and substitution of pumpage with imported surface water. The results of each simulation were evaluated with respect to the results of the baseline simulation. By comparing the two simulations, systematic errors that affect both simulations equally were eliminated.

Pumpage Increase

If recent trends continue, ground-water pumping in the Salinas Valley will probably continue to increase. Two steady-state simulations were done to determine the effects of 20 years of increased pumpage at two different rates. In both simulations, pumpage in the confined part of the Pressure Area was assumed to increase at a noncompounded annual rate of 0.5 percent. This low rate was chosen because nearly all the arable land in that area is already in production. After 20 years, annual pumpage in that area would be 10 percent greater than annual pumpage during 1970-81. Growth rates of 1.0 and 3.0 percent were evaluated for the remaining areas of the basin. These growth rates corresponded to cumulative 20-year increases of 20 and 60 percent in the annual pumping rate.

The calculated water levels for the two simulations are shown in figures 17 and 18. They reflect mean hydrologic conditions that would exist after 20 years of pumpage increase. A comparison of these water levels with the water levels for 1970-81 (fig. 10) indicates that increased annual pumpage causes large water-level declines in the East Side Area and in the coastal part of the Pressure Area. In the East Side Area, water levels declined 10 to 20 feet after 1.0 percent increase in pumpage and 20 to 60 feet after 3.0 percent increase. After 1.0 percent increase, water levels declined 5 to 10 feet throughout the Pressure Area and less than 5 feet in the Forebay and Upper Valley Areas. Three percent increase caused declines of 10 to 20 feet in the Pressure Area and 5 feet or less in the Forebay and Upper Valley Areas. The zero-water-level contour retreated 2 and 4 miles up the valley for the 1 and 3 percent cases, respectively. Table 4 shows the increases in river seepage and seawater intrusion that resulted from the two simulations of projected pumpage increase.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EXPLANATION

—210— POTENTIOMETRIC CONTOUR – Shows altitude at which water level would have stood in tightly cased wells. Contour interval is 5 and 10 feet. Datum is sea level

——— GROUND-WATER BASIN BOUNDARY

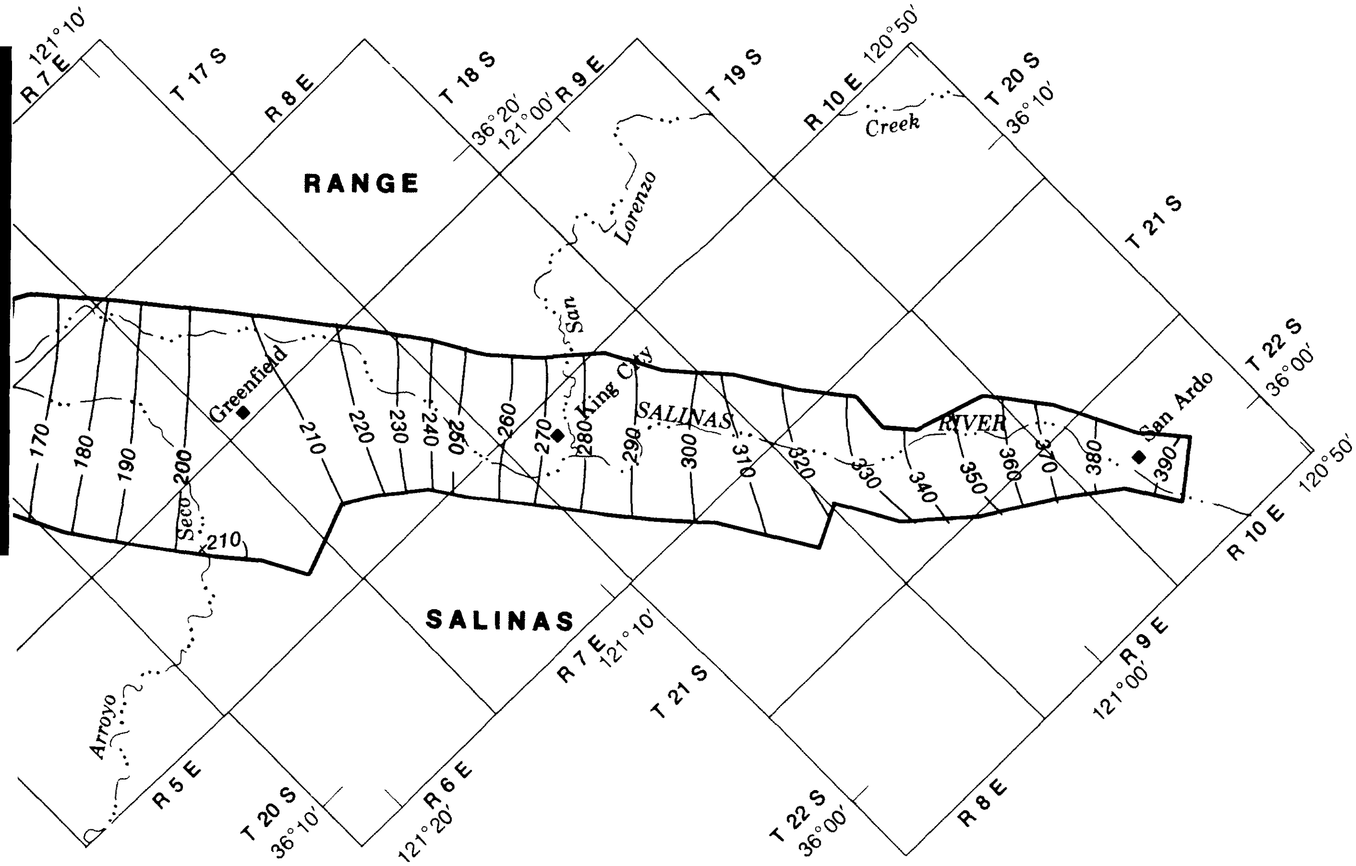
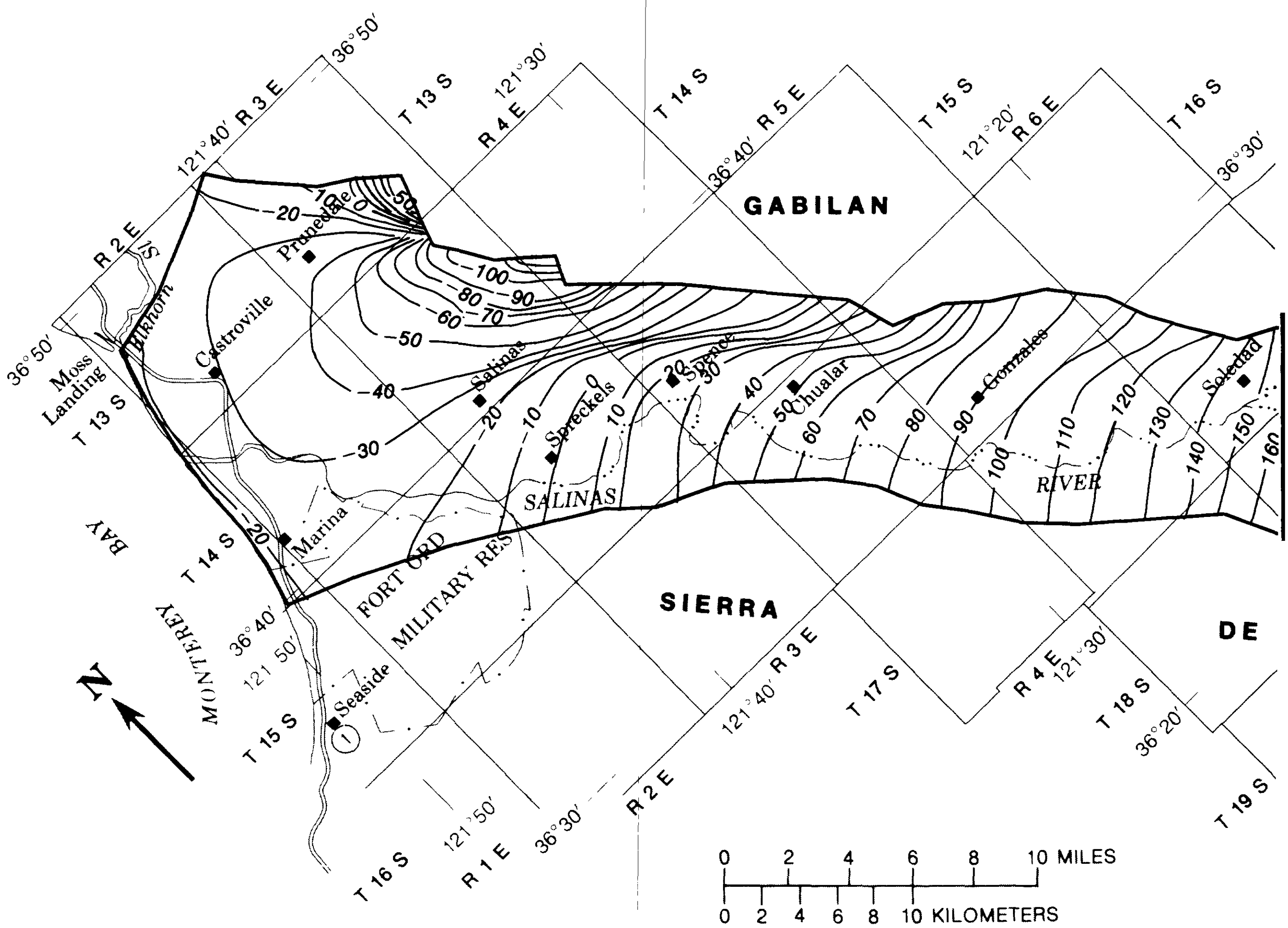


FIGURE 17. — Simulated mean water levels following 20 years of projected agricultural pumpage increase at 1 percent per year (0.5 percent in confined area).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EXPLANATION

——200—— POTENTIOMETRIC CONTOUR – Shows altitude at which water level would have stood in tightly cased wells. Contour interval is 10 feet. Datum is sea level

———— GROUND-WATER BASIN BOUNDARY

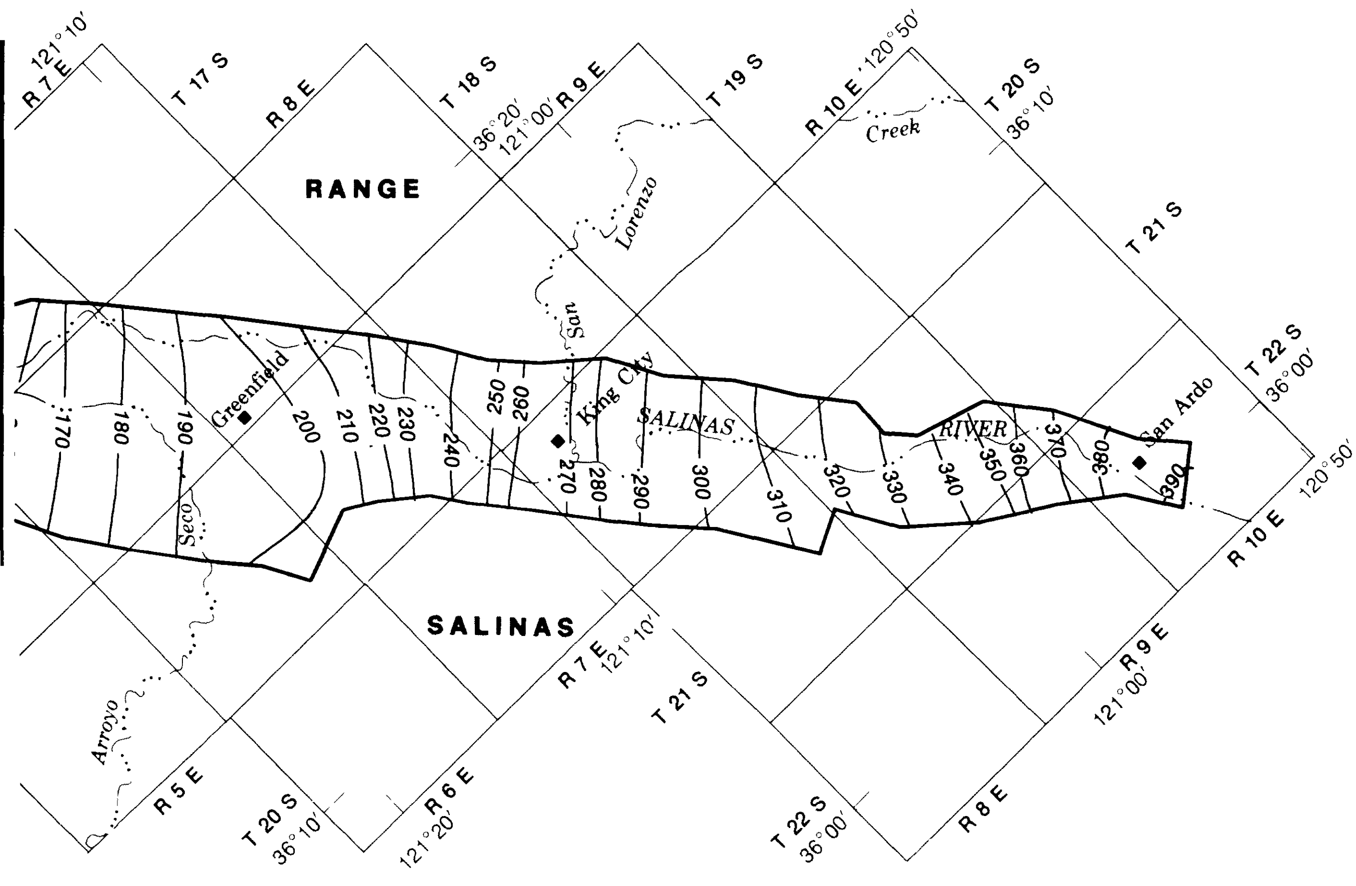


FIGURE 18. – Simulated mean water levels following 20 years of projected agricultural pumpage increase at 3 percent per year (0.5 percent in confined area).

TABLE 4.--*Comparison of rates of Salinas River recharge and seawater intrusion for 1970-81 with those following 20 years of projected pumpage increase*

Simulations	Total agricultural pumpage (acre-ft/yr)	Seawater intrusion (acre-ft/yr)	Salinas River recharge (acre-ft/yr)
Baseline	512,200	18,900	214,300
After pumpage increase[1]			
20 years, 1 percent	604,000	23,600	266,600
20 years, 3 percent	766,000	30,800	356,700

[1]Noncompounded annual pumping rate; rate is 0.5 percent in confined area.

Pumpage Decrease

Three steady-state simulations were done to determine the effects of various amounts of pumpage decrease in different areas of the valley. The simulations included the following: 10 percent decrease in pumpage throughout the valley, 10 percent in the East Side and Pressure Areas only, and 30 percent in the East Side and Pressure Areas only. Municipal and agricultural pumpages were both decreased by the indicated percentage.

The input and results of the three simulations are listed in table 5, and the simulated water levels are shown in figures 19 to 21. The results of the simulations indicate that decreases in annual pumpage decrease the rate of seawater intrusion. Results also indicate that seawater intrusion is much more sensitive to pumpage decreases in the East Side and Pressure Areas than in the Forebay and Upper Valley Areas. Decreasing pumpage by 25,000 acre-ft/yr (10 percent) in the East Side and Pressures Areas caused a decrease in seawater intrusion of 3,700 acre-ft/yr. The effect of including the Forebay and Upper Valley areas in the pumpage decrease--an additional decrease of 27,700 acre-ft/yr in basinwide pumpage--was an additional decrease in seawater intrusion of only 200 acre-ft/yr.

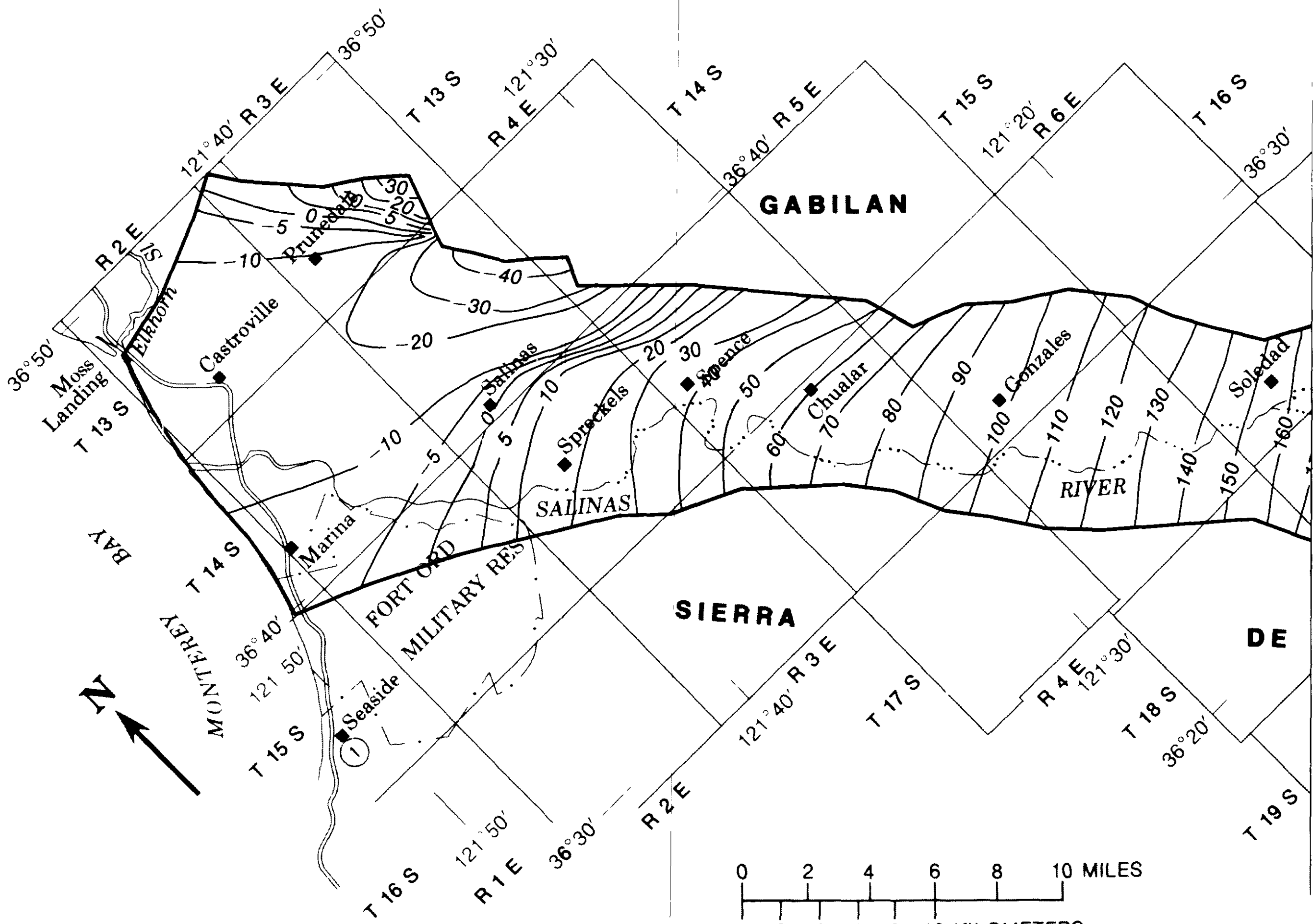
Decreasing pumpage by 77,400 acre-ft/yr (30 percent) in the East Side and Pressure Areas caused a decrease in seawater intrusion of 10,800 acre-ft/yr. As in the 10-percent case, the volume of pumpage decrease was much greater than the associated decrease in seawater intrusion. This relation exists because the decreases in pumpage cause proportional decreases in recharge from all sources, and in most areas of the valley, the river is the major source of recharge. In those areas, pumpage decreases primarily cause decreases in river recharge.

TABLE 5.--*Input and results of pumpage decrease simulations*

[Values rounded to nearest 100 acre-ft/yr]

Variable	Simulations			
		Pumpage decrease (acre-ft/yr)		
	Baseline	10 percent valleywide	10 percent East Side and Pressure Area	30 percent East Side and Pressure Area
Input				
Municipal pumpage, total for valley (acre-ft/yr)	22,300	20,100	20,400	16,500
Gross agricultural pumpage (acre-ft/yr)				
Upper Valley Area[1]	123,400	111,100	123,400	123,400
Forebay Area[1]	150,200	135,200	150,200	150,200
East Side Area[1]	101,700	91,500	91,500	71,200
Pressure Area				
Confined area[2]	102,900	92,600	92,600	72,000
Other areas[1]	34,000	30,600	30,600	23,800
Total	512,200	461,000	488,300	440,600
Results				
Recharge from Salinas River (acre-ft/yr)	214,300	184,200	200,700	172,300
Seawater intrusion (acre-ft/yr)	18,900	15,000	15,200	8,100

[1]Irrigation-return fraction is 0.40.
[2]Irrigation-return fraction is 0.26. For map of this area, see figure 2.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0 2 4 6 8 10 KILOMETERS

EXPLANATION

—— 220 —— POTENTIOMETRIC CONTOUR – Shows altitude at which water level would have stood in tightly cased wells. Contour interval is 5 and 10 feet. Datum is sea level

———— GROUND-WATER BASIN BOUNDARY

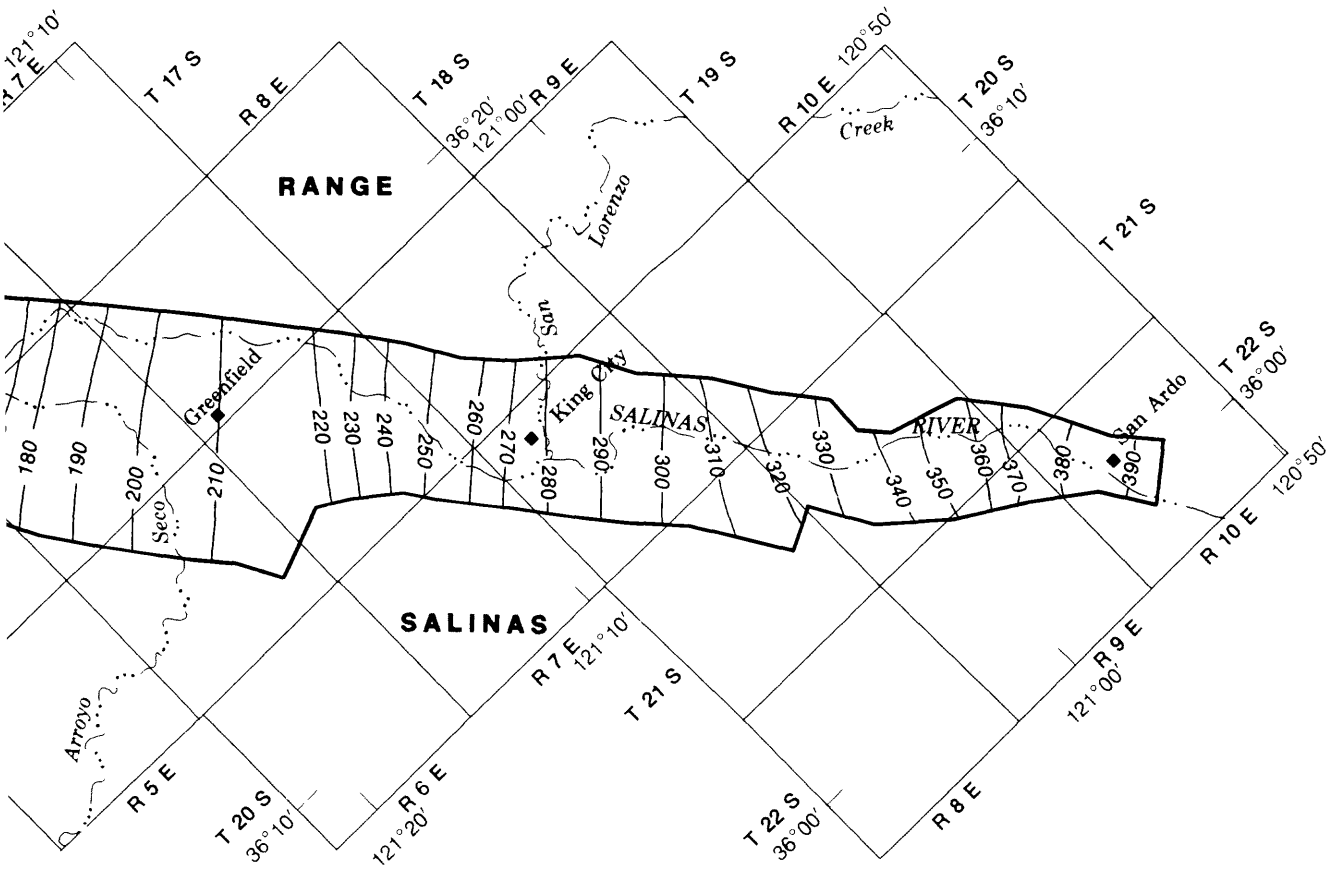
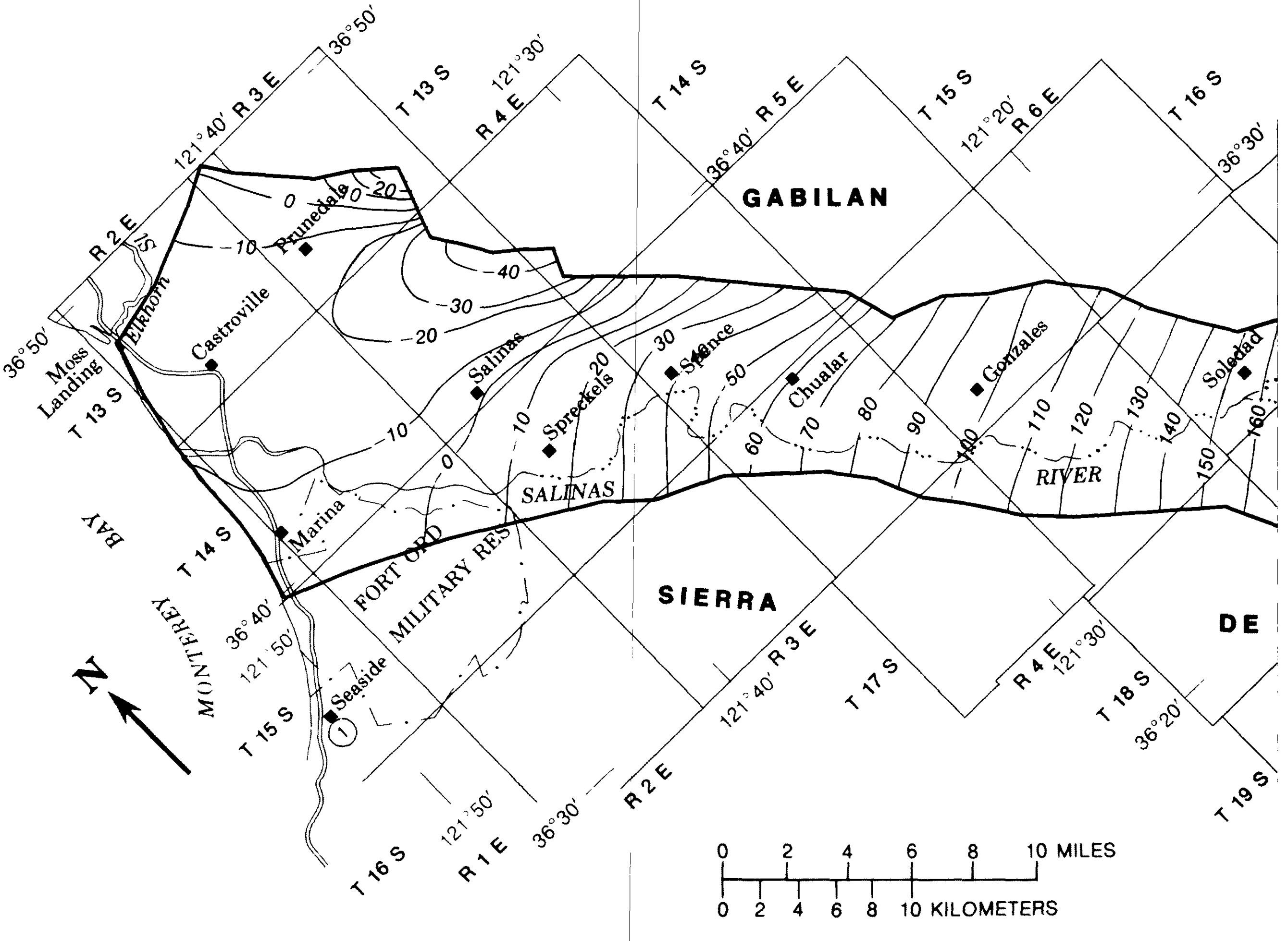


FIGURE 19. – Simulated mean water levels when agricultural and municipal pumpage are decreased throughout the valley by 10 percent of baseline values.



GABILAN
SIERRA
DE
SALINAS
RIVER
FORT ORD
MILITARY RES
MONTEREY
BAY
Moss Landing
Elkhorn
Castroville
Prunedale
Salinas
Spreckels
Spence
Chualar
Gonzales
Soledad
Marina
Seaside
N
0 2 4 6 8 10 MILES
0 2 4 6 8 10 KILOMETERS

EXPLANATION

——200—— POTENTIOMETRIC CONTOUR – Shows altitude at which water level would have stood in tightly cased wells. Contour interval is 10 feet. Datum is sea level

———— GROUND-WATER BASIN BOUNDARY

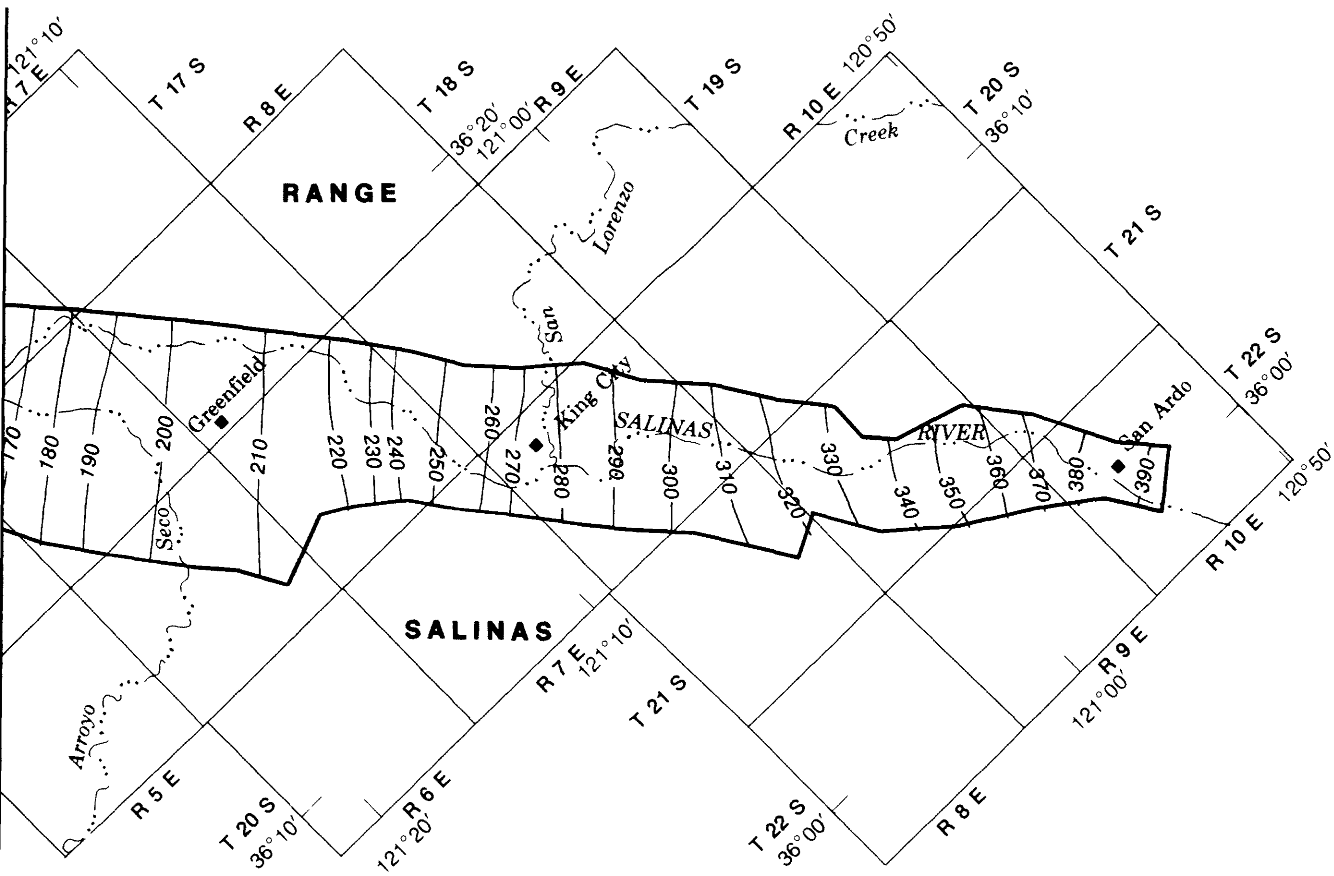
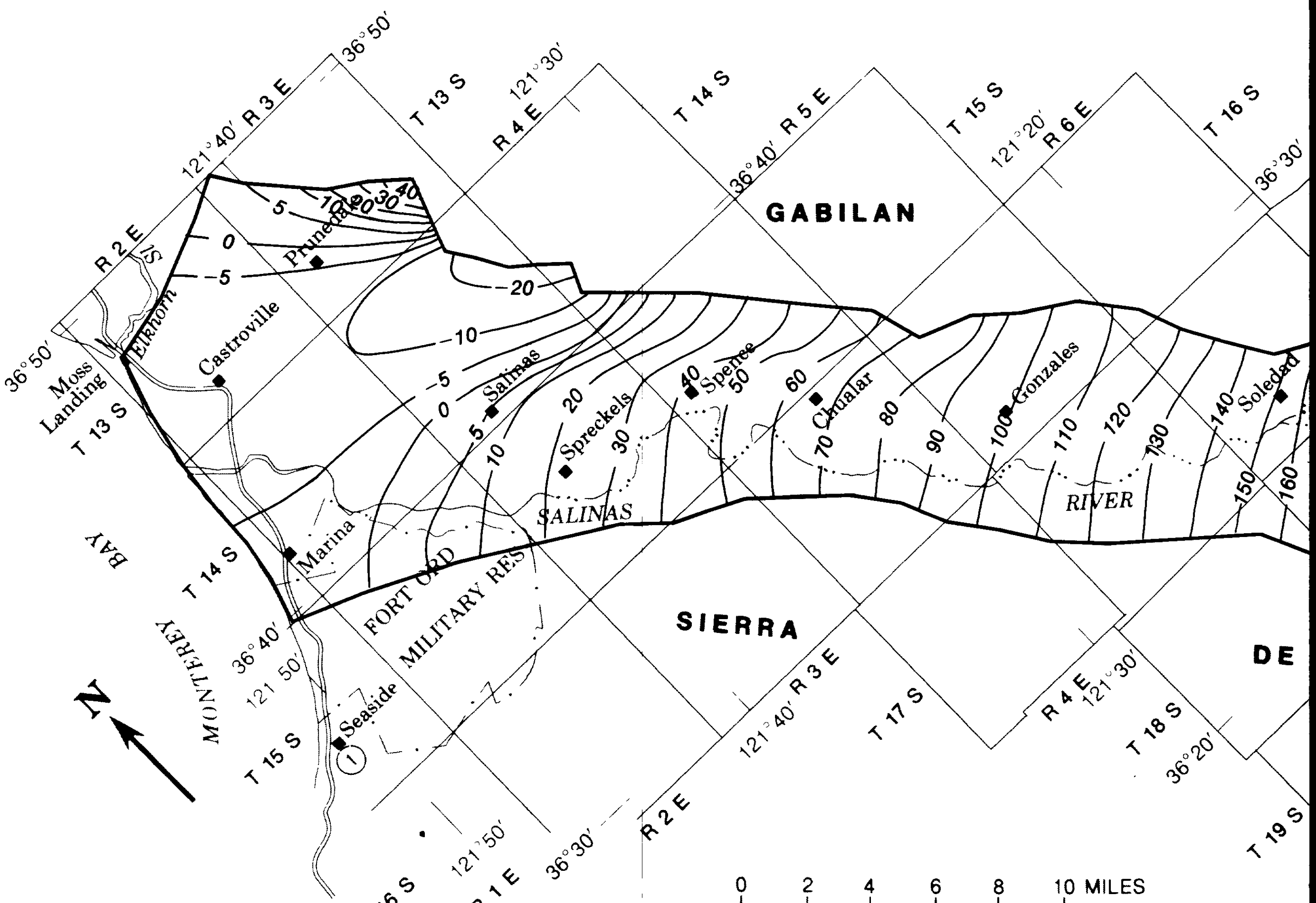


FIGURE 20. – Simulated mean water levels when agricultural and municipal pumpage are decreased in the East Side and Pressure Areas by 10 percent of baseline values.


GABILAN
SIERRA
DE
MONTEREY BAY
SALINAS RIVER
FORT ORD MILITARY RES
Moss Landing
Castroville
Prunedale
Salinas
Spreckels
Spence
Chualar
Gonzales
Soledad
Marina
Seaside
Elkhorn
T 13 S
T 14 S
T 15 S
T 16 S
T 17 S
T 18 S
T 19 S
R 1 E
R 2 E
R 3 E
R 4 E
R 5 E
R 6 E
36°50′
36°40′
36°30′
36°20′
121°50′
121°40′
121°30′
121°20′
0 2 4 6 8 10 MILES
0 2 4 6 8 10 KILOMETERS

EXPLANATION

— 170 — POTENTIOMETRIC CONTOUR – Shows altitude at which water level would have stood in tightly cased wells. Contour interval is 5 and 10 feet. Datum is sea level

———— GROUND-WATER BASIN BOUNDARY

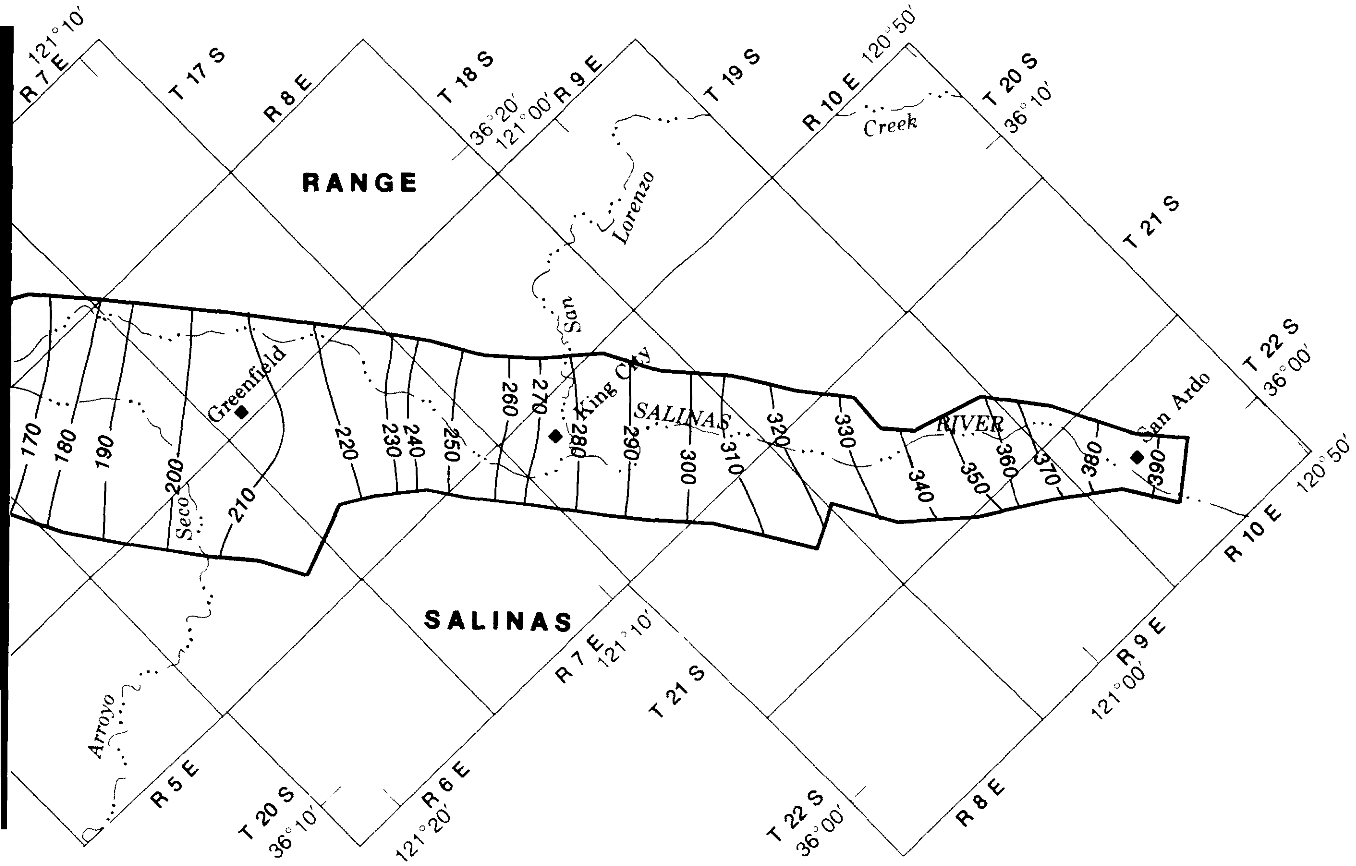


FIGURE 21. – Simulated mean water levels when agricultural and municipal pumpage are decreased in the East Side and Pressure Areas by 30 percent of baseline values.

Surface-Water Importation

Another possible water-management alternative simulated by the model is the importation of surface water to areas near the coast. One of the proposed delivery sites is the Castroville Service Area, which includes 9,000 acres of agricultural land near the city of Castroville. The location of the service area is shown in figure 22. In order to identify the optimum scope of a surface-water delivery project, several simulations were done in which water was delivered to different parts of the service area. Five geographic subareas of the Castroville Service Area were identified. Four of these, called zones 1 through 4, corresponded to the areas of partial and total seawater intrusion in the "180-foot" and "400-foot" aquifers (see fig. 22). Also, the part of the service area northwest of State Highway 1 was identified as a convenient potential management subarea. Delivery of surface water for municipal needs also was investigated. Again, a variable number of cities was included in the different simulations. The potential water-delivery sites were Castroville, Marina, and the Fort Ord military base.

An assumption was made that surface-water supply for the delivery project would be made available by releasing additional water from the two existing reservoirs upstream from the study area. Furthermore, shortages of supply were assumed to occur in drought years, and that the frequency of shortfall periods would be greater for larger delivery projects. Estimates of shortfall frequencies used in the analysis were made by CH2M-Hill, Inc. (written commun., January 27, 1984). In the simulations, local ground water was assumed to be used during shortfall periods.

The delivery of surface water to the service area was simulated by decreasing local ground-water pumpage by an amount equal to the volume delivered. Deep percolation of applied surface water was assumed not to occur. The increases in Salinas River flow that would result from the delivery of the reservoir water were not simulated because earlier sensitivity analysis indicated that the effects of the flow increases would be negligible.

Six simulations were done to determine the effects of including different combinations of agricultural areas and municipalities in the surface-water delivery area. The first four simulations showed the effects of the deliveries with respect to the 1970-81 baseline period. The final two simulations used estimated municipal pumpages for the year 2020 to predict the future consequences of including Marina and Fort Ord in the delivery project.

In the first simulation, 94.9 percent of the pumpage in zone 1 of the Castroville Service Area was eliminated and replaced with imported surface water. The remaining 5.1 percent of the original pumpage represents the amount of pumpage that would be required to provide a standby water supply during periods of drought. Actually, the standby pumping rate would be at the full baseline rate, but would occur only 5.1 percent of the time. For long-range planning purposes, however, the net effect of sporadic pumping can be simulated by a steady-state analysis in which 5.1 percent of the pumpage occurs continuously.

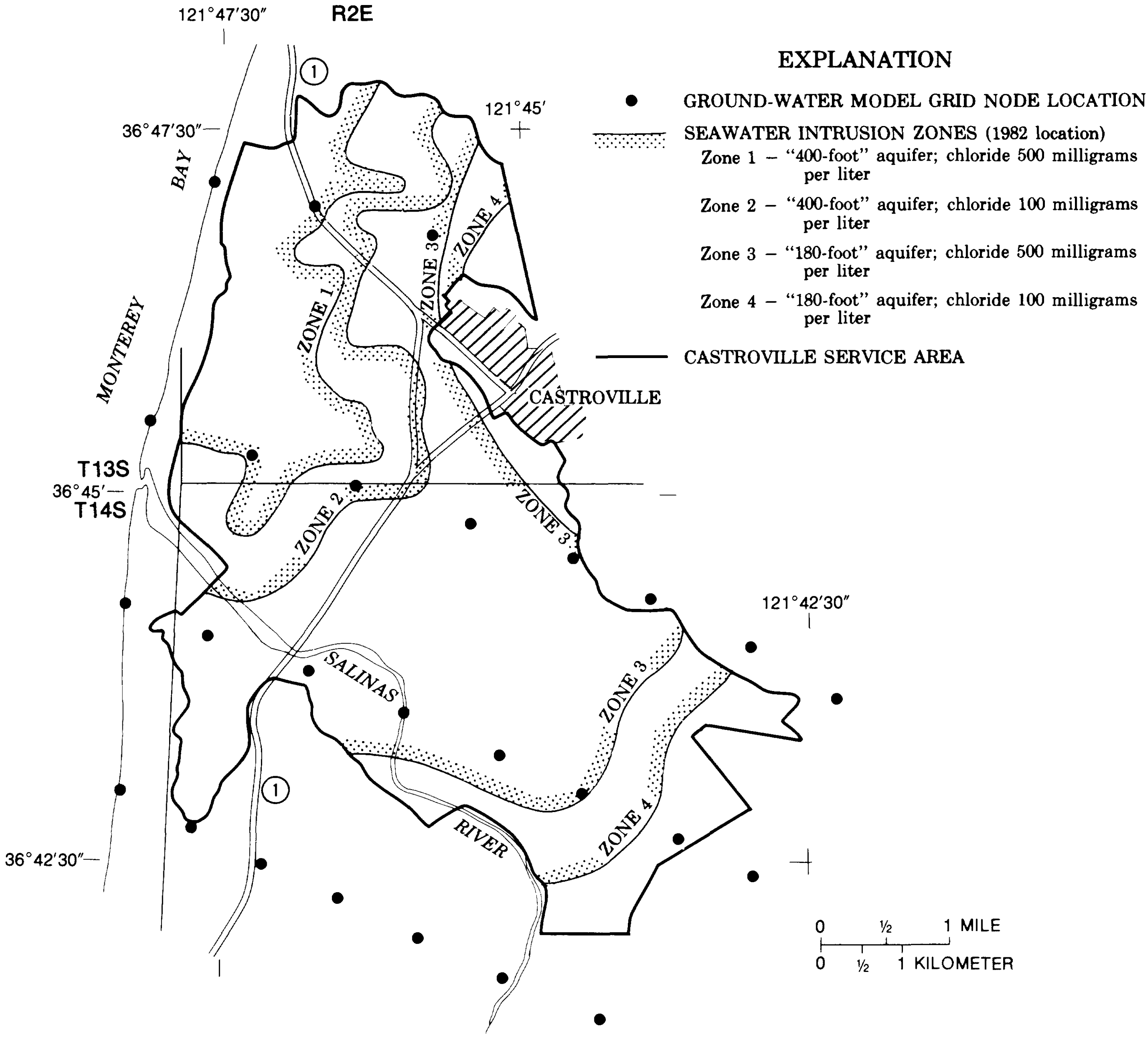


FIGURE 22. — Areal extent of seawater intrusion in the "180-foot" and "400-foot" aquifers in the Castroville Service Area.

In simulation 2, 94.9 percent of the pumpage was eliminated from the part of the service area northwest of State Highway 1. In simulation 3, all but 93.1 percent of the agricultural pumpage in zones 1 through 4 was eliminated; municipal pumpage for the city of Castroville also was reduced by 93.1 percent. Simulation 4 was similar to simulation 3, except that it included Marina and Fort Ord in the delivery project and that 91.7 percent of pumpage was eliminated.

Simulation 5 represented a "baseline" simulation for the year 2020 and served primarily as a basis for comparison with simulation 6. Estimates of municipal pumpage for the year 2020 were derived from an extrapolation of estimates for the year 2000 made by the Monterey County Flood Control and Water Conservation District (1984). Agricultural pumpage for simulations 5 and 6 was assumed to remain at 1970-81 baseline levels. Simulation 6 differed from simulation 5 only in that Marina and Fort Ord were included in the delivery project. Pumpage decreases were 93.1 percent and 91.1 percent for simulations 5 and 6, respectively. Table 6 summarizes the data and results of the six simulations. The simulated water levels near the coast are shown in figures 23 to 28. Water levels in the Forebay and Upper Valley Areas were essentially unchanged from their 1970-81 baseline configuration (see fig. 12).

The results of the simulations showed that replacing locally pumped ground water with imported surface water in any of the potential project delivery areas caused a significant decrease in the rate of seawater intrusion. Also, as would be expected, greater quantities of surface-water importation resulted in larger decreases in the rate of seawater intrusion. Simulation 1, which involved the smallest quantity of surface-water importation--2,534 acre-ft/yr--decreased seawater intrusion from 18,900 to 17,500 acre-ft/yr. Simulation 4, which involved the largest quantity of surface-water importation--24,052 acre-ft/yr--decreased seawater intrusion from 18,900 to 7,400 acre-ft/yr.

As in earlier simulations of pumpage decreases, none of the surface-water delivery simulations succeeded in completely eliminating seawater intrusion. Coincidentally, the greatest decreases in intrusion achieved in the two sets of simulation were similar. A pumpage decrease of 30 percent throughout the East Side and Pressure Areas decreased seawater intrusion to slightly less than one-half of the intrusion during base-line conditions. The delivery of surface water to zones 1 through 4, Fort Ord, and the cities of Castroville and Marina produced nearly the same results.

A final simulation was done to assess the feasibility of completely halting seawater intrusion by decreasing pumpage. All agricultural pumpage northwest of the city of Salinas was eliminated, as was municipal pumpage for Castroville, Marina, and Fort Ord. These pumpage decreases totaled 71,000 acre-ft/yr. The results of the simulation indicated that such a measure would not only eliminate seawater intrusion, but would create a ground-water outflow of 5,100 acre-ft/yr to the ocean. Figure 29 shows the area of pumpage elimination and the resulting simulated water levels. The large decrease in pumpage near the coast allowed recharge from the Salinas River to establish a ground-water mound between Monterey Bay and the pumping trough in the East Side Area. The mound created a seaward water-level gradient which prevented seawater intrusion.

TABLE 6.--*Input and results of surface-water importation simulations*

[na, not applicable]

Variable	Baseline simulation	Surface-water importation simulation					
		1	2	3	4	5	6
Input							
Agricultural water use (acre-ft/yr)							
Area served by water delivery project (see fig. 14)	na	zone 1	(1)	zones 1-4	zones 1-4	zones 1-4	zones 1-4
Reference period for pumpage	1970-81	1970-81	1970-81	1970-81	1970-81	1970-81	1970-81
Original pumpage for area	na	2,670	8,593	18,772	18,772	18,722	18,722
Imported water	0	2,534	8,155	17,477	17,213	17,477	17,101
Residual pumpage[2]	na	136	438	1,295	1,559	1,259	1,671
Municipal water use							
Area served by project	na	none	none	Castroville	Castroville Marina Fort Ord	Castroville	Castroville Marina Fort Ord
Reference period for pumpage	1970-81	1970-81	1970-81	1970-81	1970-81	2020	2020
Original pumpage for area							
Entire Salinas Valley	22,322	22,322	22,322	22,322	22,322	41,123	41,123
Castroville	717	717	717	717	717	1,500	1,500
Marina and Fort Ord	6,742	6,742	6,742	6,742	6,742	12,000	12,000
Imported water							
Castroville	0	0	0	668	657	1,397	1,367
Marina and Fort Ord	0	0	0	0	6,182	0	10,932
Residual pumpage[2]							
Castroville	na	na	na	49	60	103	133
Marina and Fort Ord	na	na	na	na	560	na	1,068
Total imported water (acre-ft/yr)	0	2,534	8,155	18,145	24,052	18,874	29,400
Residual pumping percentage[2]	na	5.1	5.1	6.9	8.3	6.9	8.9
Results							
Salinas River recharge (acre-ft/yr)	214,300	214,300	213,000	209,100	206,600	221,300	217,100
Seawater intrusion (acre-ft/yr)	18,900	17,500	14,800	10,900	7,400	16,800	10,400

[1]Area northwest of State Highway 1.
[2]Residual pumpage is the quantity of original pumpage not replaced by imported surface water.

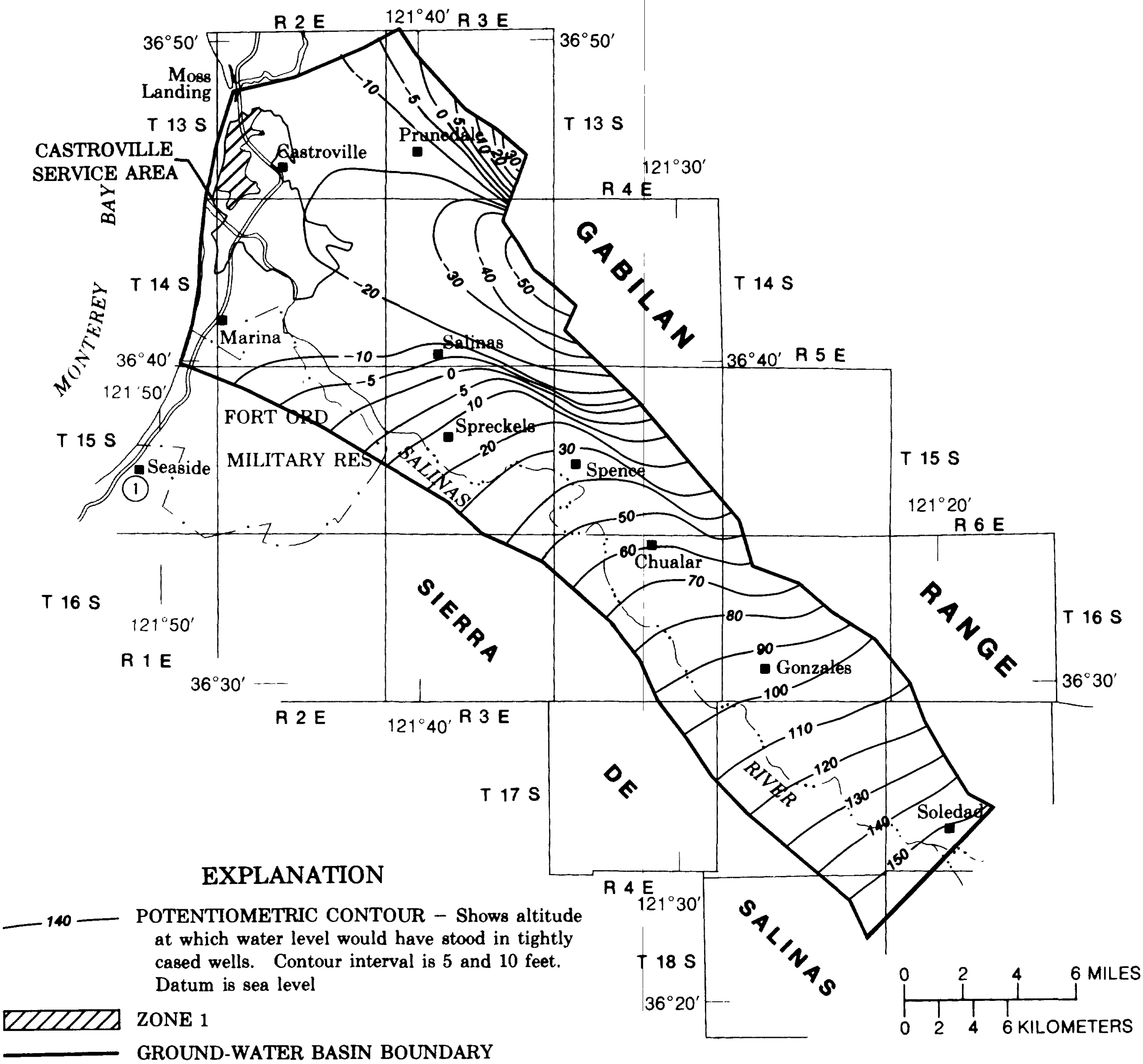


FIGURE 23. – Simulated mean water levels when annual pumpage is decreased by 94.9 percent in zone 1 in the Castroville Service Area.

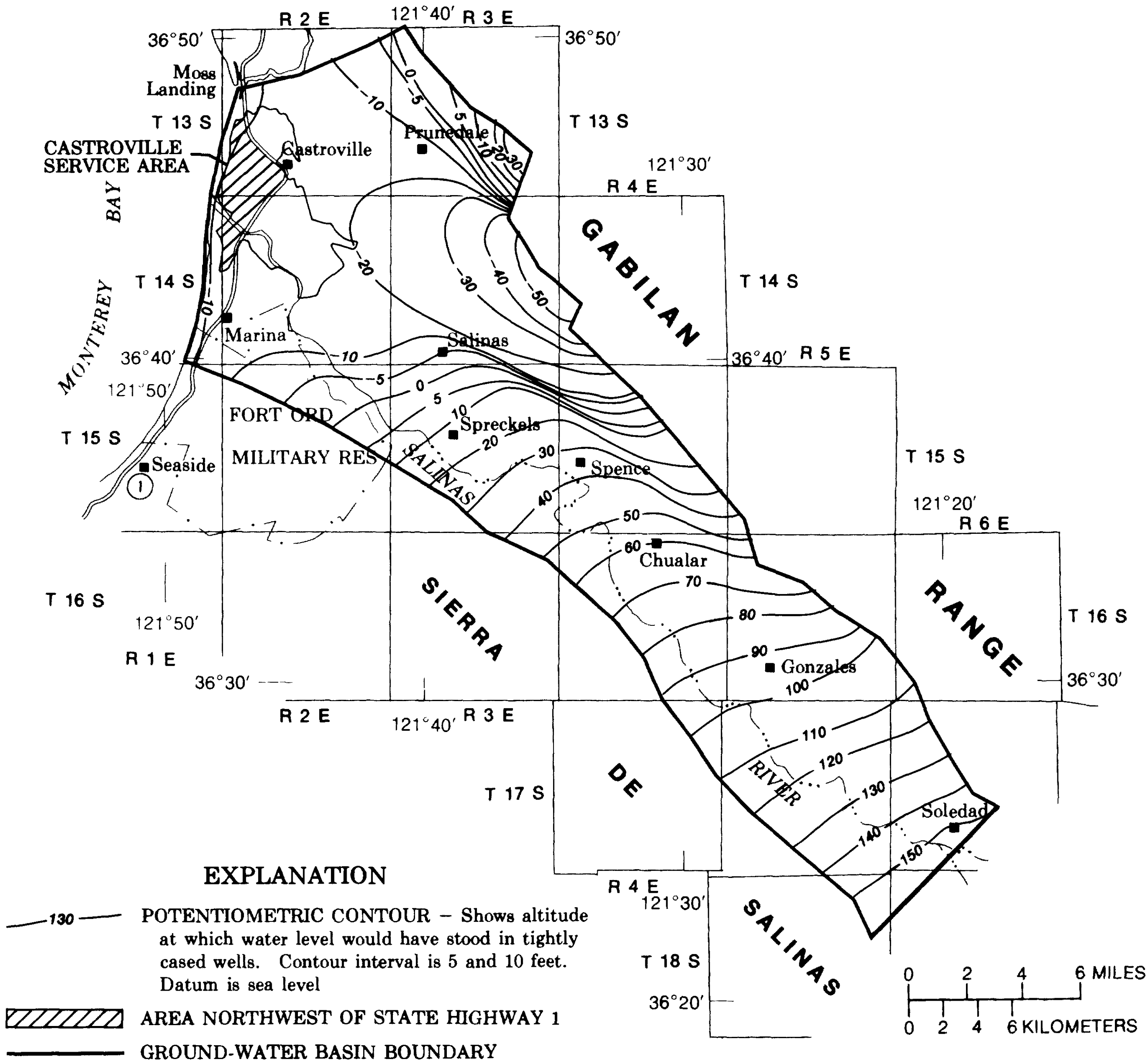


FIGURE 24. – Simulated mean water levels when annual pumpage is decreased by 94.9 percent northwest of State Highway 1 in the Castroville Service Area.

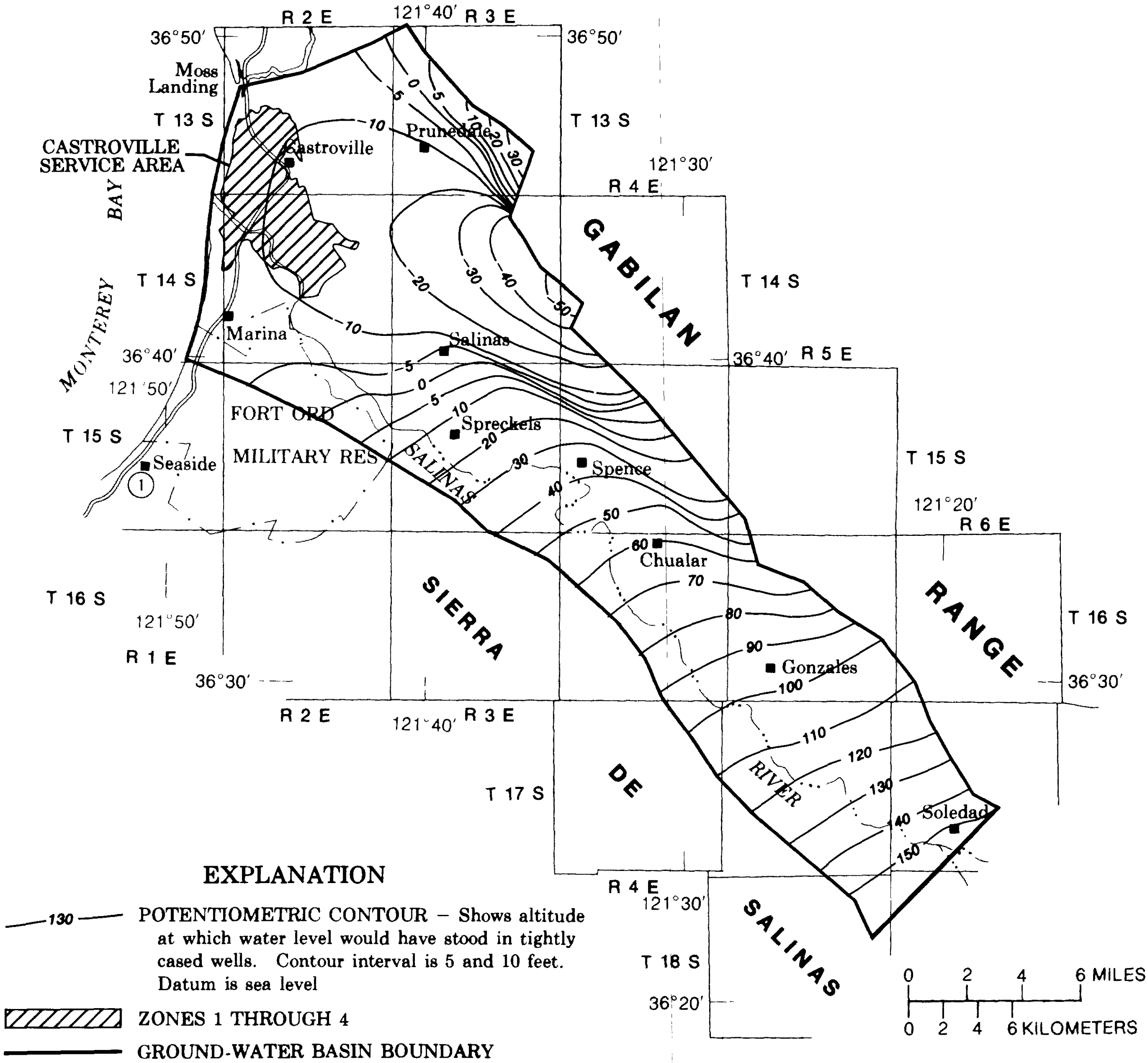


FIGURE 25. — Simulated mean water levels when annual pumpage is decreased by 93.1 percent in zones 1-4 in the Castroville Service Area and in the city of Castroville.

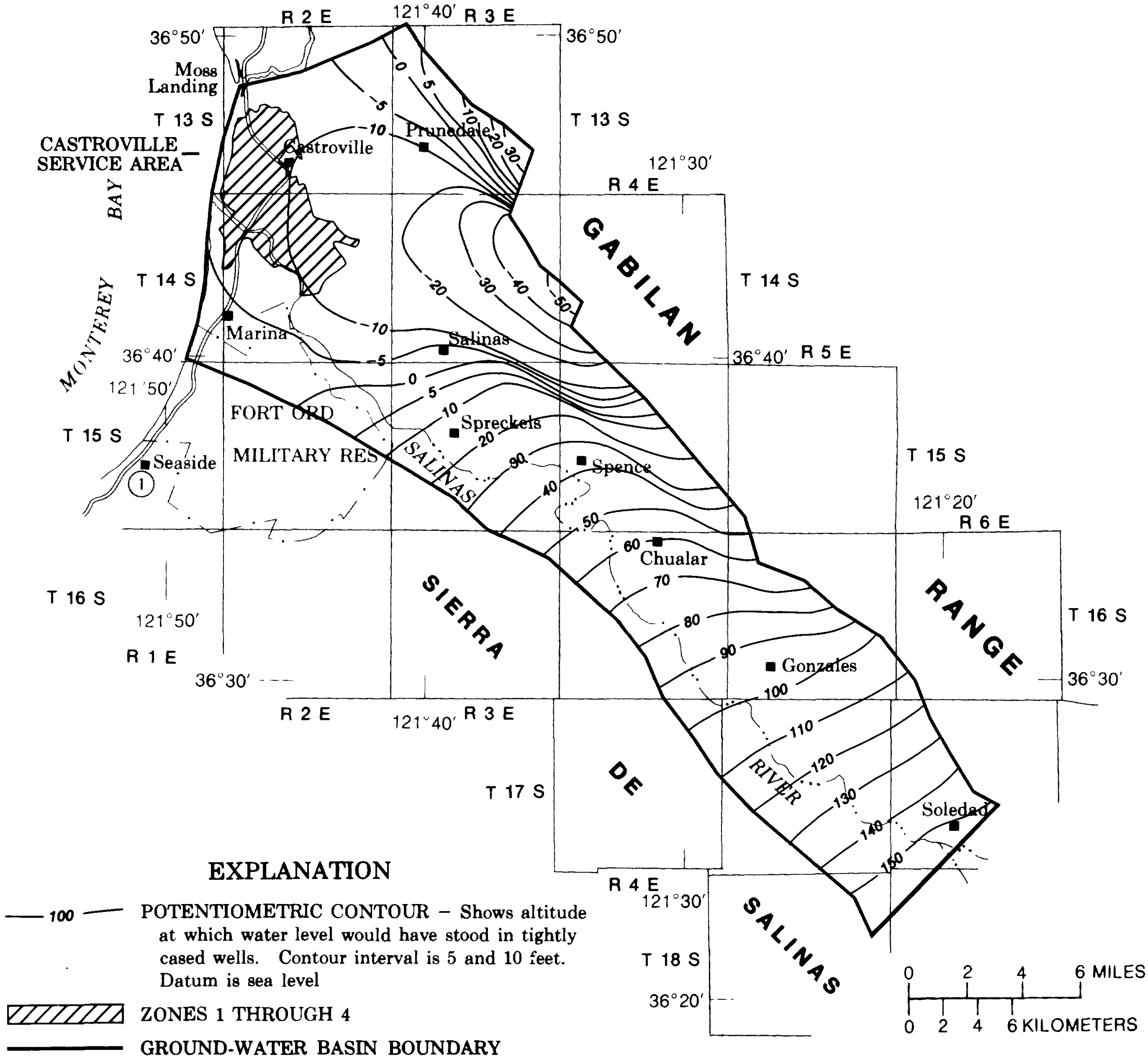


FIGURE 26. — Simulated mean water levels when annual pumpage is decreased by 91.7 percent in zones 1-4 in Castroville Service Area, Fort Ord, and in the cities of Castroville and Marina.

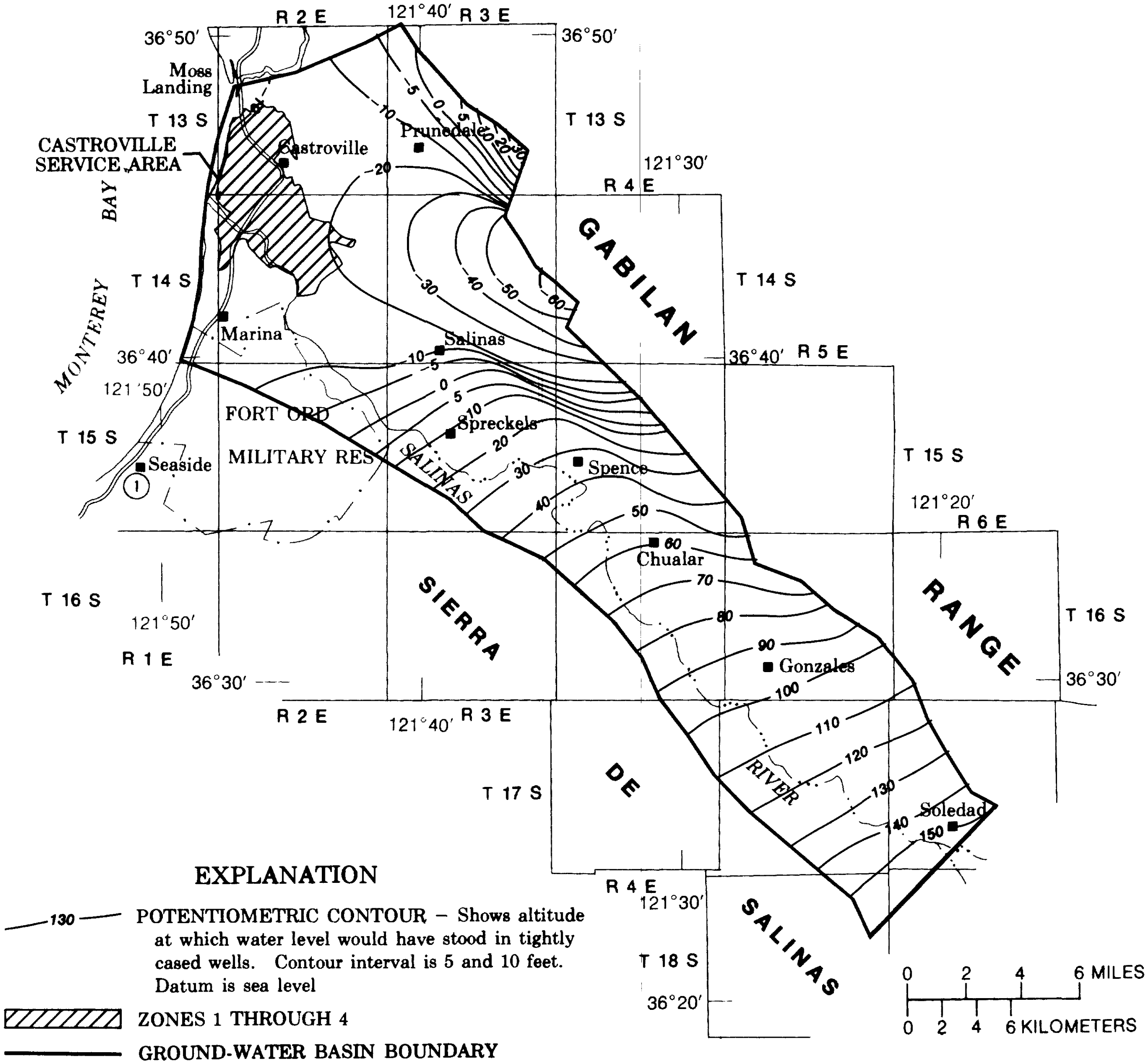
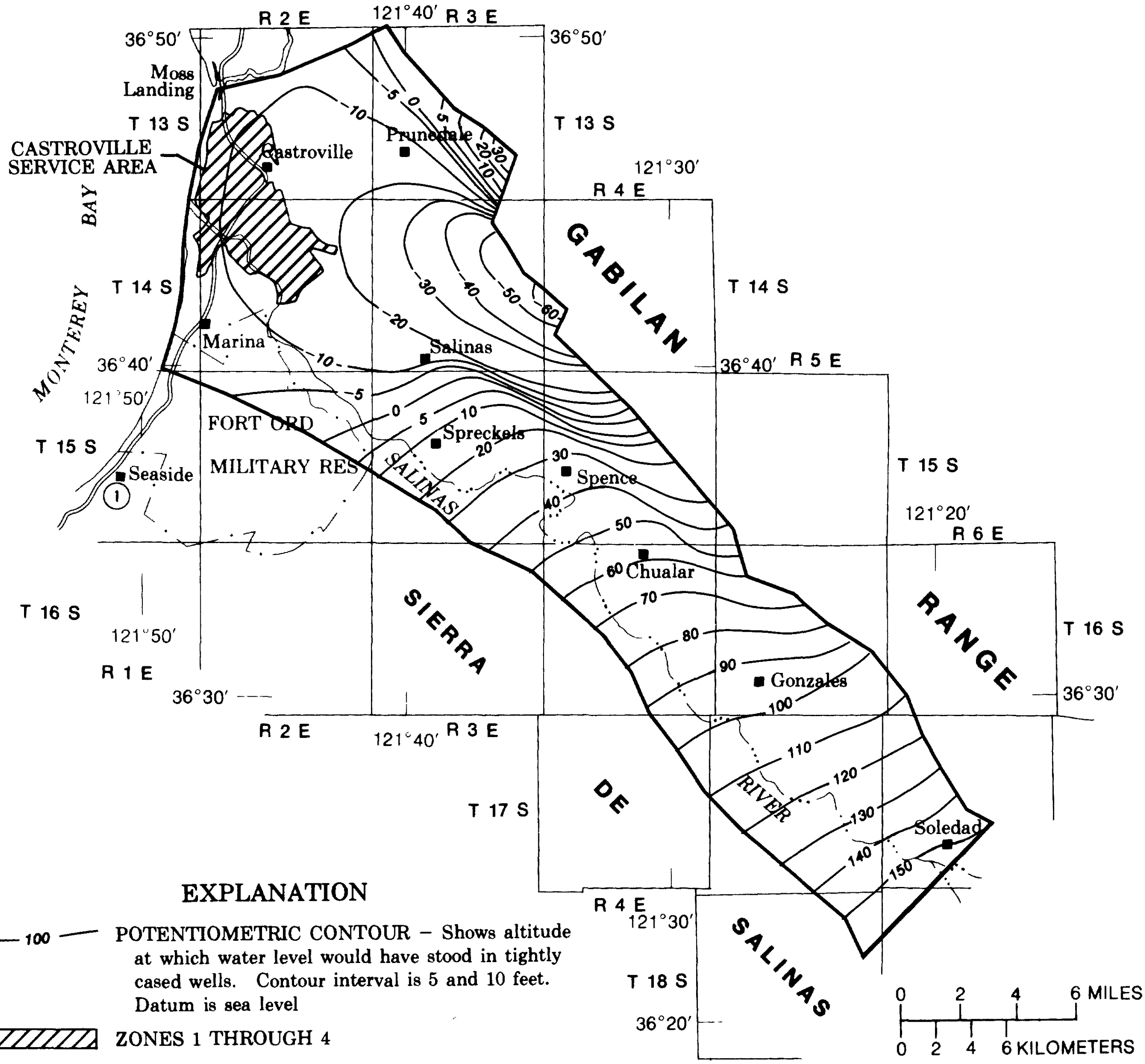


FIGURE 27. – Simulated mean water levels for the year 2020 when annual pumpage is decreased by 93.1 percent in zones 1-4 in the Castroville Service Area and in the city of Castroville.



EXPLANATION

100 — POTENTIOMETRIC CONTOUR – Shows altitude at which water level would have stood in tightly cased wells. Contour interval is 5 and 10 feet. Datum is sea level

ZONES 1 THROUGH 4

GROUND-WATER BASIN BOUNDARY

FIGURE 28. – Simulated mean water levels for the year 2020 when annual pumpage is decreased by 91.1 percent in zones 1-4 in the Castroville Service Area, Fort Ord, and in the cities of Castroville and Marina.

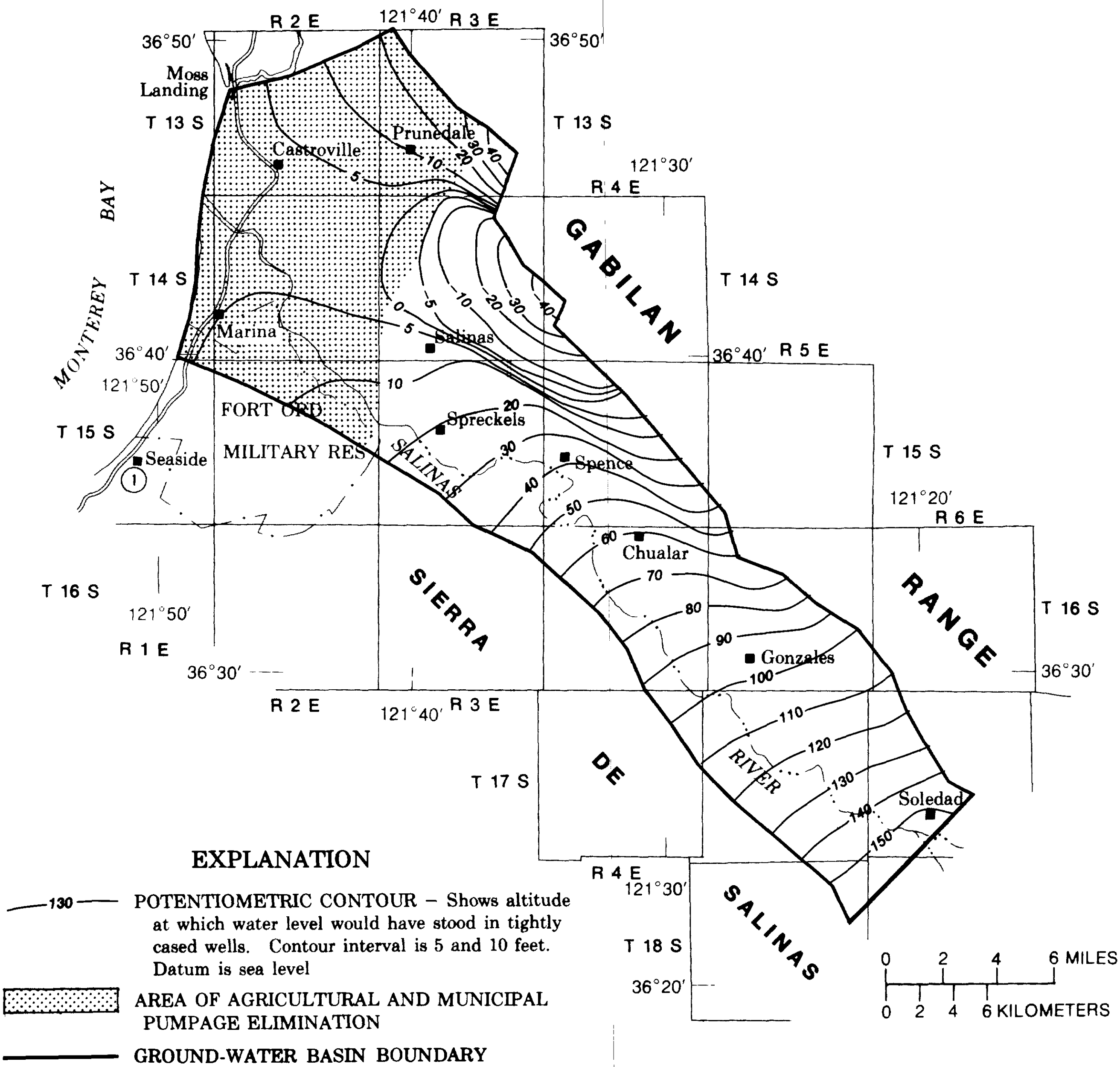


FIGURE 29. – Simulated mean water levels when all pumpage is eliminated between the city of Salinas and Monterey Bay.

Evaluation of Alternatives

One approach to evaluating the management simulations is to compare the different alternatives on the basis of their hydrologic efficiency. A measure of this efficiency is the ratio of decrease in pumpage to decrease in seawater intrusion. For example, a ratio of 1.0 means that seawater intrusion is decreased by 1 acre-ft/yr for every acre-foot per year of pumpage reduction. The smaller the ratio, the more efficient the water-management alternative. The hydrologic efficiencies of the simulated alternatives presented in table 7 show that pumpage decreases near the coast decrease seawater intrusion much more effectively than pumpage decreases farther inland. The most efficient water-management alternative was to decrease the municipal pumpages of Marina and Fort Ord. A decrease in agricultural pumpage in the Castroville Service Area was the next most efficient alternative, followed by a decrease in municipal pumpage for the city of Castroville. The differences in efficiencies for these three alternatives are slight and may not be significant. All three alternatives, however, are much more efficient than widespread decreases in pumpage throughout the Pressure and East Side Areas.

SUMMARY

The Salinas Valley is located in the coastal mountains of central California and extends approximately 70 miles from San Ardo to the Pacific Ocean. The valley ranges from 3 to 10 miles in width and is underlain by a continuous body of permeable alluvium composed of interlayered alluvial fans, marine sediments, and fluvial deposits. The ground water in the alluvium is unconfined except in the center of the valley within about 15 miles of the coast. Extensive agricultural development during the last 60 years has been attended by high rates of ground-water pumping. Pumping has caused the decline of ground-water levels in many parts of the valley and the influx of seawater into aquifers near the coast.

A two-dimensional finite-element digital model was used to analyze the ground-water hydrology of the Salinas Valley and to determine the hydrologic effects of alternative water-management plans. An earlier digital model of the Salinas Valley ground-water basin was completed by Durbin and others (1978). Many of the algorithms and much of the data used in that model were retained in the present one. Numerous changes were made, however, including modification of the finite-element grid, and revisions in the methods used to estimate small stream recharge, agricultural and municipal pumpage, and ground-water inflow.

TABLE 7.--*Comparison of the efficiencies of the simulated water-management alternatives in decreasing seawater intrusion*

[Numbers are rounded to the nearest 100. Efficiency ratio: Ratio of decrease in pumpage to decrease in seawater intrusion]

Water-management alternative	Total basinwide pumpage decrease (acre-ft/yr)	Decrease in seawater intrusion (acre-ft/yr)	Efficiency ratio
Pumpage decrease			
10 percent, valleywide	53,400	3,900	13.69
10 percent, East Side and Pressure areas	25,800	3,700	6.97
30 percent East Side and Pressure areas	77,400	10,800	7.17
Surface-water importation			
Simulation 1 (zone 1)	2,500	1,400	1.79
Simulation 2 (area northwest of State Highway 1)	8,200	4,100	2.00
Simulation 3 (zones 1-4 plus Castroville)	18,100	8,000	2.26
Simulation 4 (zones 1-4 plus Castroville, Ft. Ord, and Marina)	24,100	11,500	2.10
Simulation 6 (zones 1-4 plus Castroville, Ft. Ord, and Marina, 2020)	[1]10,500	[1]6,400	1.67

[1]The decreases for simulation 6 are with respect to the results of simulation 5. They represent the incremental reductions resulting from the addition of Marina and Fort Ord to a water-delivery project serving zones 1 through 4 and Castroville in the year 2020.

The model was calibrated to simulate measured flows and water levels from October 1970 through September 1981. The calibrated hydraulic conductivity ranged from 10 to 120 ft/d. Calibrated storage coefficients ranged from 0.005 to 0.306. Because of delayed storage properties in the aquifer, two different sets of storage coefficients were calibrated, one for simulation of seasonal water-level changes and the other for simulation of long-term changes. Other variables adjusted during calibration were irrigation-return flow, riverbed infiltration rate coefficients, the head-dependent boundary leakance factor, areal extent of the confined area, and ground-water inflow from the Pancho Rico Formation.

The steady-state calibration of the model generally produced a good match between simulated and measured water levels for the 1970-81 baseline period. Seventy percent of the simulated water levels were within 9 feet of the measured water levels; 90 percent were within 22 feet. A significant amount of model error can be attributed to small-scale spatial variability of hydrogeologic properties, which is not simulated by the model, and to the inherent inability of the two-dimensional model to simultaneously simulate measured water levels from two different depth horizons in the confined area.

The ground-water flow regime during the 1970-81 baseline period was dominated by agricultural pumpage and river recharge. The water budget during that period, as indicated by the calibrated model, consisted of inflow and outflow each totaling an annual average of 559,500 acre-ft/yr. Inflow included recharge from the Salinas River (about 38.3 percent), deep percolation of irrigation water (34.0 percent), recharge from the Arroyo Seco (16.7 percent), recharge from small streams (4.2 percent), seawater intrusion (3.4 percent), ground-water inflow (2.3 percent), and recharge from direct precipitation (1.1 percent). Outflow consisted of agricultural pumpage (91.5 percent), municipal pumpage (4.0 percent), and riparian phreatophyte evapotranspiration (4.5 percent).

A sensitivity analysis was done to determine the stability of the model results in response to changes in selected model input variables. Because agricultural pumpage is much larger than any other inflow or outflow, small uncertainties in estimated pumpage or irrigation-return flow were associated with significant uncertainties in some of the results. For example, a decrease in irrigation-return flow percentage in unconfined areas from 40 to 34 caused increases of 11 and 6 percent in the simulated rates of river seepage and seawater intrusion, respectively. In terms of percent change, seawater intrusion was more sensitive than river seepage to variations in model inputs. A 6.6-percent increase in Salinas River inflow, for example, resulted in a -1.7-percent change in seawater intrusion and a +0.15-percent change in river seepage.

The calibrated model was used to determine the effects of several prospective water-resources management alternatives. A management policy of inaction was assumed to result in continuing increases in agricultural water use. Twenty years of projected pumpage growth at a noncompounded annual rate of 1.0 percent (0.5 percent in the confined area near the coast) resulted in average water-level declines of about 10 feet in most areas northwest of Greenfield. Water levels in the East Side Area pumping trough declined as much as 20 feet, but water levels upstream of Greenfield declined by less than 5 feet. The corresponding rate of seawater intrusion increased by 4,700 acre-ft/yr, or 25 percent.

Model simulations to evaluate other water-management alternatives indicated that seawater intrusion is much more sensitive to pumpage decreases near the coast than to decreases farther inland. A uniform decrease of 10 percent in pumpage throughout the valley, which constitutes a loss of 53,400 acre-ft/yr of water supply, resulted in a decrease of only 3,900 acre-ft/yr in seawater intrusion. In contrast, eliminating 2,500 acre-ft/yr of pumpage from a 2,000-acre area near the coast (zone 1 of the Castroville Service Area) caused a proportionately large decrease of 1,400 acre-ft/yr in seawater intrusion. Although all the management alternatives resulted in smaller rates of seawater intrusion, only one alternative succeeded in halting it entirely. Completely eliminating all pumpage between Salinas and the coast--a decrease of 71,000 acre-ft/yr--resulted in elevated ground-water levels near the coast and a net outflow of 5,100 acre-ft/yr of ground water to the sea.

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